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I, KIM MARSHALL, MANAGER EXAMINATION SUPPORT AND SALES, hereby certify that the annexed is a true copy of the Provisional specification in connection with Application No. PP 4250 for a patent by LA TROBE UNIVERSITY filed on 22 June 1998.

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AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant(s):

LA TROBE UNIVERSITY

Invention Title:

IMPROVED DATA TRANSMISSION

The invention is described in the following statement:

IMPROVED DATA TRANSMISSION

The present invention relates to improved data transmission and relates particularly but not exclusively to an improved method, apparatus and system for data transmission (and/or reception) with (i) improved out-of-band power leakage (ii) improved performance in multipath channels and (iii) improved interference that would otherwise result from frequency offset.

Transmission/reception may occur either by baseband transmission/reception or by carrier transmission/reception. The present invention is applicable to both baseband and carrier systems.

MCM (multicarrier modulation) data transmission works on the principle of dividing the data stream into several parallel data streams and transmitting each data stream on a respective subcarrier. Therefore only a small proportion of the total data is carried on each subcarrier. Using N subcarriers effectively increases the symbol period by a factor of N. This allows the problem of intersymbol interference to be significantly reduced.

In MCM systems, mutually overlapping subcarrier spectra are allowable as the MCM subcarriers are all mathematically orthogonal to each other over one symbol period. Mathematically, this is achieved by the use of an orthogonal transform.

Difficulties associated with the implementation of MCM systems provide a disincentive to their practical application. For instance, MCM systems are particularly sensitive to differences in the frequency of the local oscillator at the transmitter, and the local oscillator

at the receiver. This frequency difference is often termed the local carrier frequency offset, or simply frequency offset. Acceptable performance can only be achieved when the local carrier frequency offset is within a very small percentage of the subcarrier spacing. Sensitivity increases with the number of subcarriers yet the benefits of using MCM are only obtained when a significant number of subcarriers are used.

Designing sufficient frequency accuracy is usually not practical. Even if frequency accuracy were achievable, Doppler shifts introduced through relative motion of transmitter and receiver pose a significant problem in many applications (e.g. mobile and satellite applications). Doppler phenomena may also occur if the transmitter and receiver are stationary relative to each other (e.g. Doppler reflections of television signals from moving aircraft).

Furthermore, present MCM systems suffer a lack of bandwidth containment: the form of the power spectrum roll-off of the consolidated MCM signal is $1/(fN)^2$ where f is the frequency and N is number of subcarriers. This relatively gradual roll-off is an impediment to efficient spectrum usage. MCM signals that are adjacent in the frequency domain must be spaced far enough apart that they do not interfere with each other. This problem may be alleviated to some extent by increasing the number of subcarriers. This, however, is only a partial solution as (a) it does not alter the form of the power roll-off, (b) it increases ICI (intercarrier interference) due to increased sensitivity to frequency offsets, and (c) it increases the computational complexity associated with the orthogonal transform.

The abovementioned problems associated with prior art

MCM systems (namely, out-of-band power leakage, performance degradation in multipath channels and intercarrier interference due to frequency offset) are well known and familiar to those skilled in the art. These problems remain a barrier to the practical and widespread implementation of MCM systems. Persons skilled in the art recognize the benefit of resolving these problems because their resolution provides an otherwise superior transmission system.

Despite these significant disadvantages, there has been considerable interest in providing MCM systems for a number of applications. This is because of the benefits that may be potentially achieved by an appropriate MCM system. These advantages include (a) efficient spectral usage (b) high data transfer (c) robustness to impulse noise (d) robustness to multipath fading. MCM potentially provides a much needed elegant solution to the problem of providing a robust, efficient transmission scheme at high data rate.

OFDM (orthogonal frequency division multiplexing) is one of a class of MCM schemes characterized by the use of a discrete Fourier transform to generate equally spaced and overlapping subcarrier channels. In contrast with ordinary FDM systems, OFDM is a form of FDM that has overlapping spectra. Much of the prior art related to MCM systems is described specifically in relation to OFDM systems, despite potentially broader application to MCM systems in general.

A recent paper by Zhao and Häggman ("Sensitivity to Doppler Shift and Carrier Frequency Errors in OFDM Systems - The Consequences and Solutions" *IEEE 46th Vehicular Technology Conference*, Atlanta, April 1996, pp. 1563-1568) suggests using two representations of the input data (one the negative of the other) in order to

reduce ICI. The system proposed by Zhao and Häggman is not analyzed in a way that may be readily generalized and there is no indication that it could be generalized. Furthermore, there is no suggestion in this paper of mapping data to overlapping groups of subcarriers.

The performance of the system proposed by Zhao and Häggman with respect to frequency offset is equivalent to known cosine roll-off windowing methods. However, this is not recognized in the Zhao and Häggman paper.

The performance of the system proposed by Zhao and Häggman is greatly improved over performance achievable using conventional OFDM systems but has many problems due to its limited nature.

Some embodiments of the invention have features that attempt to address this decrease in effective data rate.

Embodiments of the present invention in which representations of input data are weighted with polynomial coefficients to independently modulate a group of subcarriers may have desirable attributes such as:

- reduction of intercarrier interference (ICI) due to frequency offset or Doppler shift;
- reduction of intercarrier interference due to intersymbol interference;
- much steeper spectral roll-off, so that there is much less out-of-band power;
- concentration of energy in the middle of each symbol period so the intersymbol interference (ISI) resulting from delayed echoes of preceding symbols has much lower total power; and
- reduction of equalizer complexity due to concentration of intercarrier interference (ICI) in the time domain.

Despite these above significant advantages that may be achieved, there are also certain disadvantages that arise:

- the effective data rate is reduced as the number of independent signals that are modulated is reduced by a factor of two, three or more depending on the code used; and
- the distribution of instantaneous signal amplitude is no longer substantially Gaussian as there is an increased likelihood of high amplitude signals.

The problem of a reduction in effective data rate does not apply to other embodiments of the present invention in which there is provided coding means and/or delay means that can be used in certain circumstances to increase effective data rate. This occurs as transmitted symbols are overlapped in the frequency domain and/or time domain to alleviate the disadvantage of reduced effective data rate.

Despite the significant advantages that may be secured by independently modulating input data, a throughput penalty is incurred as the number of subcarriers required increases as the number of weighted representations of an input data increases.

Overlapping transmission in the time domain may involve the use of overlapping transmission of transmission symbols. Such methods purposely introduces a known amount of intersymbol interference which can be interpreted at a receiver through the use of appropriate techniques.

Providing overlapping transmission in the frequency-domain may be achievable using frequency overlapping techniques that may be compared to partial-response

signalling. However, more general methods such as in relation to the use of CDMA techniques may also be preferred in some circumstances. This requires the use of techniques that combine the requirements of embodiments of the present invention with the auto and cross correlation techniques required for CDMA codes. If the coded signal is to be directly mapped onto subcarriers, appropriate CDMA codes are required.

Secondly, some embodiments have the problem that the distribution of instantaneous signal amplitude is no longer Gaussian. There is an increased probability of high amplitude signals. The high peak-to-mean power is a significant disadvantage as it means that very linear amplifiers are required. The power distribution may be made almost Gaussian by overlapping of symbols in the time domain.

A number of authors (R. Li and G. Stette, "Time-limited Orthogonal Multicarrier Modulation Schemes", *IEEE Trans. Commun.*, vol. 43 no. 2/3/4 Feb/March/April 1995, pp. 1269-1272.; C. Muschallik, "Improving an OFDM reception using an adaptive Nyquist windowing", *IEEE Trans. Consumer Electronics*, vol. 42, no. 3, Aug. 1996; L. J. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing" *IEEE Trans. Commun.*, vol. 33 no. 7, July 1985, pp. 665-675) describe the use of windowing methods in OFDM systems to reduce the sensitivity to frequency offset.

Windowing to reduce sensitivity to frequency offset involves cyclically extending the time domain signal associated with each symbol and then shaping the resulting signal with a window function.

A number of different windows, including the Hanning

window, Kaiser window and windows with cosine roll-off have been described in the literature. All of these windows give some reduction in the sensitivity to frequency offset. All windows except the cosine roll-off window and the Hanning window (which is equivalent to a cosine window with a roll-off factor of one) have the disadvantage of introducing some ICI even when there is no frequency offset.

Embodiments of the present invention may be alternatively realised with windowing methods. However, in contrast with the literature, the windowing methods used in embodiments of the present invention involve the use of windows which are in general complex but may also be real in some cases, whereas known windowing techniques are only understood in terms of real windows only.

It is relatively straightforward to convert embodiments that use weighting methods to equivalent embodiments that use windowing methods. Embodiments that use windowing methods can also be converted to alternative embodiments that use weighting methods, though the conversion is much more difficult.

A working MCM system that overcomes the problems of known multicarrier modulation systems, including frequency offset sensitivity, lack of bandwidth containment, intersymbol interference and intercarrier interference due to intersymbol interference would have significant practical application. These applications include (a) digital transmission over the public switched telephone network (in particular its proposed use for asymmetric digital subscriber loop (ADSL) and high-rate digital subscriber line (HDSL)) (b) digital audio broadcasting (DAB) (c) digital mobile telephony (d) digital television broadcasting (e) satellite

communications (f) wireless local area networks. There are clearly many other applications to which MCM would be applicable, and the invention is clearly not restricted to those examples described above.

Besides the abovementioned applications there are a number of potential applications in the field of data storage systems such as on magnetic recording media. High bandwidth data storage technologies are increasingly using techniques initially developed in communications. Consequently there are a number of data storage applications to which the present invention is relevant.

Embodiments of the present invention are applicable to MCM systems that use any suitable scheme to modulate the subcarriers. Phase-shift keying (e.g. BPSK or QPSK or more generally M-ary PSK as well as differential PSK systems) is particularly appropriate as its use obviates the need for amplitude equalization. Quadrature amplitude modulation (QAM) is also a known technique for MCM systems. Irrespective of these considerations, embodiments of the present invention will work for any modulation scheme that will work with MCM systems generally.

Furthermore, embodiments of the present invention will work for arbitrary input data, independent of the statistical properties of the input data to be transmitted. For instance, the input data may be previously coded using an error correcting code, by source coding or by any other relevant coding scheme.

The above discussion has largely been in terms of carrier systems in which a local carrier frequency signal is used to translate the signal to be transmitted to some appropriate frequency range (eg microwave, radio

wave). However, the present invention is just as applicable to systems that rely on baseband transmission such as over coaxial cable etc. In particular, while the term "subcarrier" carries the same connotations as its use implies in the relevant art, this is in no way intended to limit the scope of this term to wireless systems. Instead, this term is fully intended to other systems, for instance where the term subchannels may be preferred in the art.

It should be appreciated that baseband systems and carrier systems of the types generally described above are referred to by persons skilled in the art as MCM systems and will be described and referred to as such in the description that follows.

The present invention attempts to address one or more of the disadvantages associated with the prior art, in particularly but not exclusively out-of-band power leakage, multipath effects and intercarrier interference.

According to a broad aspect of the invention there are provided embodiments including methods and apparatus for data transmission and reception using multi-carrier modulation in which data is encoded on groups of subcarriers weighted with a set of polynomial coefficients, and subsequently decoded with a corresponding set of polynomial coefficients.

Alternative embodiments may be provided with windowing techniques rather than weighting techniques.

Preferred embodiments may further include overlapping transmission in the time domain.

According to a further broad aspect of the invention

there are provided embodiments including methods and apparatus for data transmission and reception using multi-carrier modulation which includes overlapping transmission of symbols in the time domain and/or frequency domain.

Alternative embodiments may be provided with windowing techniques rather than overlapping transmission in the frequency domain.

Certain embodiments may include overlapping transmission in the frequency domain and in the time domain. Other embodiments may alternatively provide polynomial weighting or corresponding windowing techniques in place of overlapping transmission in the frequency domain.

SUMMARY OF THE INVENTION

According to a 1st aspect of the present invention there is provided a method for data transmission including steps of:

> receiving input data provided on input data channels;
>
> coding said input data with a coding means to produce coded data provided on coded data channels such that said coded data depends on two or more input data;
>
> transforming said coded data with an orthogonal transform to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;
>
> converting said transmitter transform output

data from a parallel format to a serial format to form transmitter aggregate data provided on a transmitter aggregate data channel;

converting said transmitter aggregate data from a digital format to an analog format in the form of an analog transmission signal suitable for transmission; and

transmitting said analog transmission signal.

According to a 2nd aspect of the present invention there is provided a method for data transmission according to said 1st aspect of the present invention wherein said step of converting said transmitter transform output data from a parallel format to a serial format further includes a step of selectively delaying and summing two or more transmitter delay data consisting of groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said transmitter delay data corresponding with different symbols of said transmitter transform output data.

According to a 3rd aspect of the present invention there is provided a method for data reception including steps of:

receiving an analog reception signal;

converting said analog reception signal from an analog format to a digital format in the form of receiver aggregate data provided on a receiver aggregate data channel;

converting said receiver aggregate data from a

serial format to a parallel format to form receiver transform input data provided on receiver transform input data channels;

transforming said receiver transform input data with an orthogonal transform to correspondingly produce estimator data provided on estimator data channels; and

estimating output data provided on output data channels from said estimator data.

According to a 4^{th} aspect of the present invention there is provided a method for data transmission according to said 3^{rd} aspect of the present invention wherein said step of converting said receiver aggregate data from a serial format to a parallel format further includes a step of selectively delaying two or more receiver delay data consisting of groups of data within said receiver transform input data representing a receiver symbol so that said orthogonal transform transforms combinations of said receiver delay data.

According to a 5^{th} aspect of the present invention there is provided a method for data transmission including steps of:

receiving input data provided on input data channels;

mathematically weighting said input data with a plurality of weighting coefficients to correspondingly produce weighted input data provided on weighted input data channels;

transforming said weighted input data with an orthogonal transform to correspondingly

produce transmitter transform output data provided on transmitter transform output data channels;

converting said transmitter transform output data from a parallel format to a serial format to form transmitter aggregate data provided on a transmitter aggregate data channel;

converting said transmitter aggregate data from a digital format to an analog format in the form of an analog transmission signal suitable for transmission; and

transmitting said analog transmission signal.

According to a 6^{th} aspect of the present invention there is provided a method for data transmission according to said 5^{th} aspect of the present invention wherein said step of converting said transmitter transform output data from a parallel format to a serial format further includes a step of selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to a 7^{th} aspect of the present invention there is provided a method for data reception including steps of:

receiving an analog reception signal;

converting said analog reception signal from an analog format to a digital format in the

form of receiver aggregate data provided on a receiver aggregate data channel;

converting said receiver aggregate data from a serial format to a parallel format to form receiver transform input data provided on receiver transform input data channels;

transforming said receiver transform input data with an orthogonal transform to correspondingly produce weighted output data provided on weighted output data channels; and

mathematically weighting and summing said weighted output data using a plurality of weighting coefficients to correspondingly produce output data provided on output data channels.

According to a 8^{th} aspect of the present invention there is provided a method for data transmission according to said 7^{th} aspect of the present invention wherein said step of converting said receiver aggregate data from a serial format to a parallel format further includes a step of selectively delaying groups of said receiver transform input data so that said orthogonal transform transforms combinations of said groups.

According to a 9^{th} aspect of the present invention there is provided a method for data transmission including the steps:

receiving input data provided on input data channels;

transforming said input data with an orthogonal transform to correspondingly

produce transmitter transform output data provided on transmitter transform output data channels;

windowing said transmitter transform output data according to a complex exponential window to correspondingly produce transmitter window output data provided on transmitter window output data channels;

coding said transmitter window output data with a coding means to produce coded data provided on coded data channels;

converting said coded data from a parallel format to a serial format to form transmitter aggregate data provided on a transmitter aggregate data channel;

converting said transmitter aggregate data from a digital format to an analog format in the form of an analog transmission signal suitable for transmission; and

transmitting said analog transmission signal;

wherein said steps of transforming and windowing are performed either once or in parallel more than once depending on said step of coding.

According to a 10^{th} aspect of the present invention there is provided a method for data transmission according to said 9^{th} aspect of the present invention wherein said step of converting said transmitter transform output data from a parallel format to a serial format further includes a step of selectively delaying and summing groups of data within said transmitter

transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to a 11th aspect of the present invention there is provided a method for data reception including the steps:

receiving an analog reception signal;

converting said analog reception signal from an analog format to a digital format in the form of receiver aggregate data provided on a receiver aggregate data channel;

converting said receiver aggregate data from a serial format to a parallel format in the form of receiver window input data provided on receiver window input data channels;

windowing said receiver window input data according to a complex exponential window to correspondingly produce receiver transform input data provided on receiver transform input data channels;

transforming said receiver transform input data with an orthogonal transform to correspondingly produce estimator data; and

estimating output data provided on output data channels from said estimator data;

wherein said steps of transforming and windowing are performed either once or in parallel more than once

depending on said step of estimating.

According to a 12^{th} aspect of the present invention there is provided a method for data transmission according to said 11^{th} aspect of the present invention wherein said step of converting said receiver aggregate data from a serial format to a parallel format further includes a step of selectively delaying groups of said receiver transform input data so that said orthogonal transform transforms combinations of said groups.

According to a 13^{th} aspect of the present invention there is provided a method for data transmission including the steps:

receiving input data provided on input data channels;

transforming said input data with an orthogonal transform to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;

windowing said transmitter transform output data according to a complex exponential window to correspondingly produce transmitter window output data provided on transmitter window output data channels;

converting transmitter window output data from a parallel format to a serial format in the form of transmitter aggregate data provided on a transmitter aggregate data channel;

converting said transmitter aggregate data from a digital format to an analog format in

the form of an analog transmission signal suitable for transmission; and

transmitting said analog transmission signal.

According to a 14th aspect of the present invention there is provided a method for data transmission according to said 13th aspect of the present invention wherein said step of converting said transmitter transform output data from a parallel format to a serial format further includes a step of selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to a 15th aspect of the present invention there is provided a method for data reception including the steps:

receiving an analog reception signal;

converting said analog reception signal from an analog format to a digital format in the form of receiver aggregate data provided on a receiver aggregate data channel;

converting said receiver aggregate data from a serial format to a parallel format in the form of receiver window input data provided on receiver window input data channels;

windowing said receiver window input data according to a complex exponential window to correspondingly produce receiver transform

input data provided on receiver transform input data channels;

transforming said receiver transform input data with an orthogonal transform to correspondingly produce output data.

According to a 16th aspect of the present invention there is provided a method for data transmission according to said 15th aspect of the present invention wherein said step of converting said receiver aggregate data from a serial format to a parallel format further includes a step of selectively delaying groups of data within said receiver transform input data so that said orthogonal transform transforms combinations of said groups of data within said receiver transform input data.

According to a 17th aspect of the present invention there is provided an apparatus for data transmission including:

input data channels to carry input data to be transmitted;

coding means to receive said input data and to produce coded data provided on coded data channels so that said coded data depends on two or more input data;

orthogonal transform means to receive said weighted input data and to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;

parallel-to-serial converting means to convert

said transmitter transform output data to transmitter aggregate data provided on a transmitter aggregate data channel;

digital-to-analog converter means to produce an analog transmission signal suitable for transmission from said transmitter aggregate data; and

transmission means to transmit said analog transmission signal.

According to a 18th aspect of the present invention there is provided an apparatus for data transmission according to said 17th aspect of the present invention wherein said parallel-to-serial converting means further includes delay means for selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to an 19th aspect of the present invention there is provided an apparatus for data reception including:

reception means to receive an analog reception signal;

analog-to-digital converter means to convert an analog reception signal to receiver aggregate data provided on a receiver aggregate data channel;

serial-to-parallel converter means to convert

said receiver aggregate data to receiver transform input data provided on receiver transform input data channels;

orthogonal transform means to receive said receiver transform input data and to correspondingly producing estimator data provided on estimator data channels;

estimating means to estimate output data from said estimator data.

output data channels to carry output data to be received.

According to a 20^{th} aspect of the present invention there is provided a method for data transmission according to said 19^{th} aspect of the present invention wherein said serial-to-parallel converter means further includes delay means for selectively delaying groups of data within said receiver transform input data representing a symbol so that said orthogonal transform transforms data consisting of combinations of said groups of said receiver transform input data.

According to a 21^{st} aspect of the present invention there is provided a method for data transmission including steps of:

receiving input data provided on input data channels;

mathematically weighting said input data with a plurality of weighting coefficients to correspondingly produce weighted input data provided on weighted input data channels;

transforming said weighted input data with an orthogonal transform to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;

converting said transmitter transform output data from a parallel format to a serial format to form transmitter aggregate data provided on a transmitter aggregate data channel;

converting said transmitter aggregate data from a digital format to an analog format in the form of an analog transmission signal suitable for transmission; and

transmitting said analog transmission signal.

According to a 22nd aspect of the present invention there is provided an apparatus for data transmission according to any one of said 21st aspect of the present invention wherein said parallel-to-serial converting means further includes delay means for selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to an 23rd aspect of the present invention there is provided an apparatus for data reception including:

reception means to receive an analog reception

signal;

analog-to-digital converter means to convert an analog reception signal to receiver aggregate data provided on a receiver aggregate data channel;

serial-to-parallel converter means to convert said receiver aggregate data to receiver transform input data provided on receiver transform input data channels;

orthogonal transform means to receive said receiver transform input data and to correspondingly producing weighted output data provided on weighted output data channels;

weighting means to mathematically weight and sum said weighted output data using a plurality of weighting coefficients to correspondingly produce output data; and

output data channels to carry output data to be received.

According to a 24th aspect of the present invention there is provided an apparatus for data transmission according to said 23rd aspect of the present invention wherein said serial-to-parallel converter means further includes delay means for selectively delaying groups of data within said receiver transform input data representing a symbol so that said orthogonal transform transforms data consisting of combinations of said groups of said receiver transform input data.

According to a 25th aspect of the present invention there is provided an apparatus for data transmission

including:

input data channels to carry input data to be transmitted;

orthogonal transform means to receive said input data and to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;

windowing means to receive said transmitter transform output data and to correspondingly produce transmitter window output data provided on transmitter window output channels according to a complex exponential window;

coding means to receive said transmitter transform output data and to produce coded data provided on coded data channels;

parallel-to-serial converting means to convert said coded data to transmitter aggregate data provided on a transmitter aggregate data channel;

digital-to-analog converter means to produce an analog transmission signal suitable for transmission from said transmitter aggregate data; and

transmission means to transmit said analog transmission signal;

wherein said orthogonal transform means and said windowing means includes either one orthogonal transform means and one windowing means or a parallel configuration of more than one orthogonal transform

means and more than one windowing means depending on said coding means.

According to a 26^{th} aspect of the present invention there is provided an apparatus for data transmission according to any one of said 25^{th} aspect of the present invention wherein said parallel-to-serial converting means further includes delay means for selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter transform output data.

According to a 27^{th} aspect of the present invention there is provided an apparatus for data reception including:

reception means to receive an analog reception signal;

analog-to-digital converter means to convert said analog reception signal to receiver aggregate data provided on a receiver aggregate data channel;

serial-to-parallel converter means to convert said receiver aggregate data to receiver window input data provided on receiver window input data channels;

windowing means to receive said receiver window input data and to correspondingly produce receiver transform input data provided on receiver transform input data channels

according to a complex exponential window;

orthogonal transform means to receive receiver transform input data and to correspondingly produce estimator data provided on estimator data channels;

estimator means to estimate said output data carried on output data channels from said estimator data; and

output data channels to carry said output data to be received.

wherein said orthogonal transform means and said windowing means includes either one orthogonal transform means and one windowing means or a parallel configuration of more than one orthogonal transform means and more than one windowing means depending on said estimator means;

According to a 28^{th} aspect of the present invention there is provided an apparatus for data transmission according to said 27^{th} aspect of the present invention wherein said serial-to-parallel converter means further includes delay means for selectively delaying groups of data within said receiver transform input data representing a symbol so that said orthogonal transform transforms data consisting of combinations of said groups of said receiver transform input data.

According to a 29^{th} aspect of the present invention there is provided an apparatus for data transmission including:

input data channels to carry input data to be transmitted;

orthogonal transform means to receive said input data and to correspondingly produce transmitter transform output data provided on transmitter transform output data channels;

windowing means to receive said transmitter transform output data and to correspondingly produce transmitter window output data provided on transmitter window output channels according to a complex exponential window;

parallel-to-serial converter means to convert said transmitter window output data to transmitter aggregate data provided on a transmitter aggregate data channel;

digital-to-analog converter means to produce an analog transmission signal suitable for transmission from said transmitter aggregate data; and

transmission means to transmit said analog transmission signal.

According to a 30th aspect of the present invention there is provided an apparatus for data transmission according to any one of said 29th aspect of the present invention wherein said parallel-to-serial converting means further includes delay means for selectively delaying and summing groups of data within said transmitter transform output data representing a transmitter symbol so that said transmitter aggregate data consists of values that are a summation of corresponding members selected from said groups of data taken from different symbols of said transmitter

transform output data.

According to a 31st aspect of the present invention there is provided an apparatus for data reception including:

reception means to receive an analog reception signal;

analog-to-digital converter means to convert said analog reception signal to receiver aggregate data provided on a receiver aggregate data channel;

serial-to-parallel converter means to convert said receiver aggregate data to receiver window input data provided on receiver window input data channels;

windowing means to receive said receiver window input data and to correspondingly produce receiver transform input data provided on receiver transform input data channels according to a complex exponential window;

orthogonal transform means to receive receiver transform input data and to correspondingly produce output data provided on output data channels; and

output data channels to carry said output data to be received.

According to a 32nd aspect of the present invention there is provided an apparatus for data transmission according to said 31st aspect of the present invention wherein said serial-to-parallel converter means further

includes delay means for selectively delaying groups of data within said receiver transform input data representing a symbol so that said orthogonal transform transforms data consisting of combinations of said groups of said receiver transform input data.

Further aspects of the present invention are provided for methods and apparatus for data transmission and reception wherein said method or apparatus for data transmission is provided by an aspect of the invention that includes a weighting step or weighting means and said method or apparatus for data reception is provided by an aspect of the invention that includes a windowing step or windowing means.

Further aspects of the present invention are provided for methods and apparatus for data transmission and reception wherein said method or apparatus for data transmission is provided by an aspect of the invention that includes a windowing step or windowing means and said method or apparatus for data reception is provided by an aspect of the invention that includes a weighting step or weighting means.

According to a 33rd aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 1st aspect of the present invention and the steps of data reception according to said 3rd aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 34th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 2nd aspect of the present invention

and the steps of data reception according to said 4th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 35th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 5th aspect of the present invention and the steps of data reception according to said 7th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 36th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 6th aspect of the present invention and the steps of data reception according to said 8th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 37th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 9th aspect of the present invention and the steps of data reception according to said 11th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 38th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 10th aspect of the present invention and the steps of data reception according to said 12th

aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 39th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 13th aspect of the present invention and the steps of data reception according to said 15th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 40th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 14th aspect of the present invention and the steps of data reception according to said 16th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 41st aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 1st or 9th aspect of the present invention and the steps of data reception according to said 11th or 3rd aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 42nd aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 2nd or 10th aspect of the present invention and the steps of data reception according to said 12th or 4th aspect of the present invention

respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 43rd aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 5th or 13th aspect of the present invention and the steps of data reception according to said 15th or 7th aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 44th aspect of the present invention there is provided a method for a data transmission and reception including the steps of data transmission according to said 6th or 14th aspect of the present invention and the steps of data reception according to said 16th or 8th aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 45th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either said 17th aspect of the present invention and one or more apparatus according to either said 19th aspects of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 46th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either said 18th aspect of the present invention and one or more apparatus according to either said 20th aspect of the present invention wherein said analog transmission signal corresponds with said analog

reception signal.

According to a 47th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either said 21st aspect of the present invention and one or more apparatus according to either said 23rd aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 48th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either said 22nd aspect of the present invention and one or more apparatus according to either said 24th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 49th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either said 25th aspect of the present invention and one or more apparatus according to said 27th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 50th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to said 26th aspect of the present invention and one or more apparatus according to said 28th aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 51st aspect of the present invention

there is provided an apparatus for data transmission and reception including one or more apparatus according to said 29^{th} aspect of the present invention and one or more apparatus according to said 31^{st} aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 52^{nd} aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to said 30^{th} aspect of the present invention and one or more apparatus according to said 32^{nd} aspect of the present invention wherein said analog transmission signal corresponds with said analog reception signal.

According to a 53^{rd} aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either of said 17^{th} or 25^{th} aspects of the present invention and one or more apparatus according to either of said 27^{th} or 19^{th} aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 54^{th} aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either of said 18^{th} or 26^{th} aspects of the present invention and one or more apparatus according to either of said 28^{th} or 20^{th} aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 55^{th} aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either of said 21^{st} or 29^{th} aspects of the present

invention and one or more apparatus according to either of said 31st or 23rd aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

According to a 56th aspect of the present invention there is provided an apparatus for data transmission and reception including one or more apparatus according to either of said 22nd or 30th aspects of the present invention and one or more apparatus according to either of said 32nd or 24th aspect of the present invention respectively wherein said analog transmission signal corresponds with said analog reception signal.

In certain embodiments it is preferred that in methods or apparatus for data transmission that rely on a windowing step or windowing means further include the use of a cyclic extension to reduce the complexity required of said orthogonal transform, and that corresponding methods or apparatus for data reception correspondingly include a contraction to recover the input data. In such corresponding embodiments it is preferred that the contraction be achieved by a element-by-element summation of corresponding lower-order and higher-order frequency coefficients of the receiver transform input data before it is input to the receiver orthogonal transform.

In certain embodiments it is preferred that in methods or apparatus for data transmission that rely on a windowing step or windowing means, said step of providing an orthogonal transform or said orthogonal transform means incorporates the use of input data that is zero where inputs are not provided from input data channels. In certain corresponding embodiments of methods or apparatus for data reception that rely of a

step of windowing or windowing means, said step of providing an orthogonal transform or said orthogonal transform means incorporates the use of output data that can be disregarded in collecting output data that estimates input data.

It is preferred that said input data provided on input data channels be provided by a symbol constellation modulation scheme.

It is preferred that in baseband data transmission, said analog transmission signal is a transmitter baseband signal that is a baseband representation of said transmitter aggregate data.

It is preferred that in baseband data transmission, said analog transmission signal has only one component to transmit said input data.

It is preferred that in carrier data transmission, said analog transmission signal is a transmitter carrier signal that is a carrier representation of the transmitter aggregate data that has been frequency shifted by multiplication by an exponential local carrier frequency.

It is preferred that in carrier data transmission said input data comprises complex data having both real and imaginary components.

It is preferred that in carrier data transmission, said transmitter carrier signal has an inphase and a quadrature component to carry real and imaginary components of the input data respectively.

It is preferred that said weighting coefficients consist of the polynomial coefficients of the form

$$(1+p_1x+p_2x^2+\ldots p_{W-1}x^{W-1})$$

It is preferred that said weighting coefficients consist of the polynomial coefficients of the form

$$(1-x)(1+g_1x+g_2x^2+\ldots g_{W-2}x^{W-2})$$

such that $p_0 = 1$, $p_1 = (g_1-1)$, $p_2 = (g_2-g_1)$, ... $p_{W-1} = (g_{W-1}-g_{W-2})$

It is preferred that said weighting coefficients consist of the polynomial coefficients of the form

$$(1-x)^{W-1}$$

where p_0 is 1, p_1 is the coefficient of x, p_2 is the coefficient of x^2 and p_j is the coefficient of x_j where j is between 0 and W-1.

In certain embodiments it is preferred that said coding means includes a coding that includes arithmetically coding two or more weighted input data.

In other embodiments it is preferred that said coding means includes a coding that collocates said weighted input data without performing any arithmetic operations.

It is preferred that said step of estimating said output data and said estimator means include maximum likelihood decoding.

It is preferred that said step of estimating or said estimating means includes the use of an equalizer to estimate said output data.

It is preferred that said step of providing an orthogonal transform and said orthogonal transform means rely on mathematical correlations between said weighted input data to reduce the computational complexity involved in computing an orthogonal transform.

It is preferred that said step of providing an orthogonal transform and said orthogonal transform means rely on mathematical correlations between said receiver transform input data to reduce the computational complexity involved in computing an orthogonal transform.

It is preferred that said step of providing an orthogonal transform and said orthogonal transform means relies on a discrete Fourier-based transform such as a discrete cosine transform or a discrete sine transform.

It is preferred that said step of providing an orthogonal transform and said orthogonal transform means relies on a discrete Fourier-based transform that is calculated according to a FFT-like algorithm.

It is preferred that said step of providing an analog-to-digital conversion and/or said step of providing an orthogonal transform include a step of filtering to filter/shape the eventual analog transmission signal as desired.

It is preferred that said analog-to-digital converter means and/or said orthogonal transform means include filtering means to filter/shape the analog transmission signal as desired.

By way of non-limiting illustrative examples, examples of a number of embodiments of the present invention will be described below so that the nature and scope of the present invention may be more clearly ascertained and understood.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a typical prior art

OFDM system.

Figure 2 is a graph representing the power roll-off of a typical prior art OFDM system. The x-axis is in frequency and the y-axis is in decibels (dB).

Figure 3 is a graph representing the complex interference coefficients demonstrating the interference characteristics of a typical prior art OFDM system in the presence of typical values of carrier frequency offset. In this example $\Delta fT = 0.2$ and $N = 16$, with phase-offset equal to zero at the beginning of the symbol period. The real components of the complex interference coefficients are represented by diamonds and the imaginary components are represented by triangles.

Figure 4A is a schematic diagram representing a data transmitter according to an embodiment of the present invention in a carrier system.

Figure 4B is a schematic diagram representing a data transmitter according to an embodiment of the present invention in a baseband system.

Figure 5A is a schematic diagram representing a data receiver according to an embodiment of the present invention in a carrier system.

Figure 5B is a schematic diagram representing a data receiver according to an embodiment of the present invention in a baseband system.

Figure 6A is a schematic diagram representing a data transmitter according to an embodiment of the present invention with a generalised mapping between input data and weighted input data in a carrier system.

Figure 6B is a schematic diagram representing a data transmitter according to an embodiment of the present invention with a generalised mapping between input data and weighted input data in a baseband system.

Figure 7 is a drawing representing examples of overlapping symbol periods according to embodiments of the present invention which include overlapping transmission in the time domain.

Figure 8A is a schematic diagram representing a data transmitter according to an embodiment of the present invention in which there is an overlapping transmission in the time domain in a carrier system.

Figure 8B is a schematic diagram representing a data transmitter according to an embodiment of the present invention in which there is an overlapping transmission in the time domain in a baseband system.

Figure 8C is a schematic drawing representing part of a data transmitter according to an embodiment of the present embodiment which uses overlapping transmission in the time domain.

Figure 9A is a schematic diagram representing a data receiver according to an embodiment of the present invention in which there is an overlapping transmission in the time domain in a carrier system.

Figure 9B is a schematic diagram representing a data receiver according to an embodiment of the present invention in which there is an overlapping transmission in the time domain in a baseband system.

Figure 9C is a schematic diagram representing part of a

data receiver according to an embodiment of the present invention that uses overlapping transmission in the time domain.

Figure 10 is a schematic diagram representing part of an estimation means in a data receiver according to an embodiment of the present invention which uses overlapping transmission in the time domain.

Figure 11 is a schematic diagram representing part of an equalizer in a data receiver according to an embodiment of the present invention which uses overlapping transmission in the time domain.

Figure 12A is a schematic diagram representing a data transmitter according to an embodiment of the present invention in which there is overlapping transmission in the frequency domain in a carrier system.

Figure 12B is a schematic diagram representing a data transmitter according to an embodiment of the present invention in which there is overlapping transmission in the frequency domain in a baseband system.

Figure 12C is a schematic diagram representing a data receiver according to an embodiment of the present invention in which there is overlapping transmission in the frequency domain in a carrier system.

Figure 12D is a schematic diagram representing a data receiver according to an embodiment of the present invention in which there is overlapping transmission in the frequency domain in a baseband system.

Figure 13A is a schematic diagram representing the effect of the coding means according to an embodiment of the present invention where each coded data depends on

two input data.

Figures 13B is a schematic diagram representing the effect of the coding means according to an embodiment of the present invention where coded data depends on three input data.

Figure 13C is a schematic diagram representing the effect of the coding means according to an embodiment of the present invention where each input data produces three coded data, and the coding means essentially collocates the weighted input data.

Figure 13D is a schematic diagram representing an alternate embodiment where the coding means provides a mapping of input data to coded data where each input data maps to three coded data, but with each depending at most on two input data.

Figure 14A is a schematic diagram representing a data system according to an embodiment of a present invention wherein weighting is unevenly distributed between the transmitter and the receiver with more subcarriers being used in the transmitter, and less in the receiver.

Figure 14B is a schematic diagram representing a data system according to an embodiment of a present invention wherein weighting is unevenly distributed between the transmitter and the receiver with less subcarriers being used in the transmitter, and more in the receiver.

Figure 15 is a simplified schematic diagram representing part of a data transmitter according to an embodiment of the present invention wherein more weighted input data channels are used to represent input data channels at the frequency edges of the data signal.

Figure 16 is a simplified schematic diagram representing part of a data transmitter according to an embodiment of the present invention wherein adjacent input data channels do not correspond with consecutively adjacent weighted input data channels.

Figure 17A is a schematic diagram representing a data system according to an embodiment of the present invention wherein an oversized orthogonal transform is used in conjunction with windowing methods in a carrier system.

Figure 17B is a schematic diagram representing a data system according to an embodiment of the present invention wherein an oversized orthogonal transform is used in conjunction with windowing methods in a baseband system.

Figure 18A is a schematic diagram representing a data system according to an embodiment of the present invention wherein a cyclic extension is used in combination with windowing methods in a carrier system.

Figure 18B is a schematic diagram representing a data system according to an embodiment of the present invention wherein a cyclic extension is used in combination with windowing methods in a baseband system.

Figure 19 is a scatterplot representing symbols received in a system having frequency offset for a typical prior art OFDM system with 64 subcarriers.

Figure 20 is a scatterplot representing symbols received in a system having frequency offset for an embodiment of the present invention that uses 64 subcarriers and linear cancellation.

Figure 21 is a scatterplot representing symbols received in a system having frequency offset for an embodiment of the present invention that uses 64 subcarriers and cubic cancellation.

Figure 22 is a graph representing the signal to ICI noise ratio of an embodiment of the present invention compared with the signal to ICI noise ratio of a typical prior art OFDM system. The y-axis is in decibels (dB) and the x-axis is in frequency offset as a proportion of the spacing between subcarriers. The upper curve is representative of a performance curve for an embodiment of the present invention that provides cubic cancellation. The lower curve is representative of a performance curve for a typical prior art OFDM system.

Figure 23A is a graph representing the power spectrum roll-off of a typical prior art OFDM system. The x-axis is in frequency and the y-axis is in decibels (dB).

Figure 23B is a graph representing the power spectrum roll-off of an embodiment of the present invention. The x-axis is in frequency and the y-axis is in decibels (dB).

GLOSSARY OF TERMS

The following notation is used throughout the description in relation to various equations.

T	symbol period of symbol on input data channels
N	size of an orthogonal transform
P	number of weighted input data
D	number of input data in symbol period
W	number of weighting coefficients for each input data

$d_{0,i} \ldots d_{D-1,i}$	input data of i-th symbol at input to weighting means
$K_0 \ldots K_{D-1}$	transmitter pre-weighting coefficients
$p_0 \ \ldots \ p_{W-1}$	transmitter weighting coefficients
$g_1 \ \ldots \ g_{W-1}$	transmitter generating polynomial coefficients
$b_{0,i} \ldots b_{N-1,i}$	transmitter coded output data or transmitter weighted output data at output of coding means or weighting means and input to orthogonal transform
$c_{0,j} \ldots c_{N-1,j}$	transmitter transform output data at output of orthogonal transform
m	number of samples between overlapping symbols in the time domain
s_k	transmitter aggregate data at output of parallel-to-serial converter and input to digital-to-analog converter
$s(t)$	transmitter baseband signal
$u(t)$	analog transmission signal
f_c	transmitter local oscillator frequency
$\exp(j2\pi f_c t)$	transmitter local carrier frequency signal
f_r	receiver local oscillator frequency
$\exp(j2\pi f_r t)$	receiver local carrier frequency signal
Δf	local oscillator frequency difference
$v(t)$	analog reception signal
$r(t)$	receiver baseband signal
r_k	receiver aggregate data at output of analog-to-digital converter and input to serial-to-parallel converter
$x_{0,i} \ldots x_{N-1,i}$	receiver transform input data of i-th symbol at output of serial-to-parallel converter and input of orthogonal transform
$y_{0,i} \ldots y_{N-1,i}$	receiver estimator data or weighted output data of i-th symbol at output of orthogonal transform and input of

	estimator or weighting and summing means
$q_0 \ldots q_{W-1}$	receiver weighting coefficients
$L_0 \ldots L_{D-1}$	receiver post-weighting coefficients
$v_{\mu,i}$	estimator means equalizer coefficients
$e_{0,i} \ldots e_{D-1,i}$	output data of i-th symbol at output of estimator
$C_0 \ldots C_{N-1}$	complex interference coefficients

Other acronyms are defined as follows and typically have the same connotation as is known in the relevant art of communications and/or signal processing.

ADC	analog-to-digital converter
BER	bit-error rate
BPF	band-pass filter
BPSK	binary phase-shift keying
CDMA	code division multiple access
DAC	digital-to-analog converter
DFT	discrete Fourier transform
DCT	discrete cosine transform
DST	discrete sine transform
FDM	frequency division multiplexing
FFT	fast Fourier transform
ICI	intercarrier interference
IDFT	inverse discrete Fourier transform
IFFT	inverse fast Fourier transform
ISI	intersymbol interference
LPF	low-pass filter
OFDM	orthogonal frequency division multiplexing
PSK	phase-shift keying
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
SNR	signal-to-noise ratio

The following features and associated reference numerals are used throughout the description in relation to

accompanying drawings.

1. weighting means 1
2. coding means 2
3. orthogonal transform 3
4. cyclic extension 4
5. windowing means 5
6. delay means 6
7. parallel-to-serial converter 7
8. digital-to-analog converter (DAC) 8
9. transmitter local carrier frequency signal $\exp(j2\pi f_r t)$ 9
10. receiver local carrier frequency signal $\exp(j2\pi f_r t)$ 10
11. analog-to-digital converter (ADC) 11
12. serial-to-parallel converter 12
13. windowing means 13
14. cyclic contraction 14
15. delay means 15
16. orthogonal transform means 16
17. estimator means 17
18. weighting means 18

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Presented in Figure 1 is a schematic diagram of a typical prior art OFDM system. This type of transmission system was developed in order to provide a high-data bandwidth efficient system for data transmission. The basic principle is to allow the spectra of the subchannels of the data transmission system to overlap in order to make better use of the available bandwidth. This is possible as the signal carried by each subcarrier is mathematically orthogonal over a symbol period as a result of the use of an orthogonal transform 3 such as a DFT.

In reference to Figure 1, input data $d_{0,i}$ ... $d_{N-1,i}$ to be transmitted is directly input to an orthogonal transform 3, the output of which is transmitter transform output data $c_{0,i}$ ... $c_{N-1,i}$ that is input directly to a parallel-to-serial converter 7. The serial output is termed transmitter aggregate data s_k that is then input to a DAC 8. The output from the DAC 8 is then a transmitter baseband signal $s(t)$.

Low pass filtering will typically be involved at some stage, usually as a combination of analog and digital methods in the DAC 8 and orthogonal transform 3 respectively. Other and/or alternative techniques of providing low pass filtering may also be used by a person skilled in the art.

The transmitter baseband signal $s(t)$ is then multiplied by a transmitter local carrier frequency signal $\exp(j2\pi f_c t)$ 9 to form an analog transmission signal $u(t)$ that is then transmitted over a transmission channel.

This transmission channel may of course be any appropriate channel, and the characteristics of the analog transmission signal $u(t)$ are chosen to accommodate the transmission channel.

The receiver receives the analog transmission signal $u(t)$ as an analog reception signal $v(t)$, and in this sense the analog reception signal $v(t)$ corresponds with the analog transmission signal $u(t)$. Of course, in the prior art systems as in embodiments of the present invention, these signals are not identical except in an ideal, noiseless transmission channel. In real systems, the analog reception signal $v(t)$ is a noisy, distorted representation of the analog transmission signal $u(t)$.

The receiver receives the analog reception signal $v(t)$

and multiplies it by a receiver local carrier frequency signal $\exp(j2\pi f_r t)$ 10 to obtain a receiver baseband signal $r(t)$. This receiver baseband signal $r(t)$ is input to a ADC 11. The output of the ADC 11 provides receiver aggregate data r_k is input to a serial-to-parallel converter 12 that provides receiver transform input data $x_{0,i}$ ... $x_{N-1,i}$ to an orthogonal transform 16. The orthogonal transform 16 then provides output data $e_{0,i}$ ... $e_{N-1,i}$ that corresponds with the input data $d_{0,i}$ ... $d_{N-1,i}$.

In the prior art as in embodiments of the present invention, the orthogonal transform 3 in the transmitter and the orthogonal transform 16 in the receiver complement each other. One is the inverse of the other. Conceptually, it is considered that the orthogonal transform 3 in the transmitter is an inverse transform to provide a mapping from the frequency domain to the time domain and the orthogonal transform 16 in the receiver is a forward transform to provide a mapping from the time domain back to the frequency domain.

In an ideal system, the output data $e_{0,i}$ ... $e_{N-1,i}$ is precisely equal to the input data $d_{0,i}$ ... $d_{N-1,i}$. However, as previously outlined, this is not the case in practical systems as are known in the prior art.

In MCM systems in which adjacent subcarriers overlap, the signal can be received without intercarrier interference if the subcarriers are mathematically orthogonal to each other.

In an OFDM receiver, the analog reception signal $v(t)$ is translated down to baseband to produce the receiver baseband signal $r(t)$. If the other carriers all beat down to frequencies that, in the time domain, have a whole number of cycles in the symbol period (T), there

is zero contribution from all these other subcarriers. Thus the subcarriers are mathematically orthogonal if the subcarrier spacing is a multiple of 1/T. This condition is a natural result of using an orthogonal transform 3 and 16 such as a DFT in order to produce the subcarrier frequencies.

Prior art MCM systems as broadly described above are deficient in three key respects.

Firstly, the power spectrum of the analog transmission signal $u(t)$ that is transmitted over the channel does not possess a steep roll-off. This is a problem because it means that an MCM signal must be sufficiently isolated in the frequency domain so that other signals do not interfere with the MCM signal and the MCM signal does not interfere with any other signals.

Figure 2 demonstrates this lack of bandwidth containment.

Prior art MCM systems in which bandwidth containment was a consideration tended to use a large number of subcarriers in order to force the power spectrum to fall off more rapidly. This approach meets with limited success as the form of the power spectrum roll-off remains the same (of the form $1/(fN)^2$). This prior art solution does not significantly decrease the power roll-off. Furthermore, increasing the number of subcarriers increases the sensitivity of the system to local carrier frequency offsets.

In most cases the number of subcarriers needed to achieve acceptable roll-off makes the system sensitive to frequency offset that leads to ICI that, in turn, results in an unacceptably high BER. Increasing the number of subcarriers also has the additional drawback

of increasing the computational complexity of the orthogonal transform 3 and 16 in the transmitter and receiver by the same factor.

Secondly, prior art systems are very sensitive to frequency differences between the transmitter local oscillator frequency f_c and the receiver local oscillator frequency f_r. This local oscillator frequency difference Δf causes a breakdown in the orthogonality of subcarriers and leads to a situation where the signal of each subcarrier interferes with the signal on each other subcarrier to a certain extent.

This local oscillator frequency difference Δf may arise due to absolute differences in the frequencies f_c and f_r and/or Doppler shifts due to relative motion of transmitter and receiver. This phenomenon of local oscillator frequency difference Δf results in ICI and may be quantitatively described by the use of complex interference coefficients $(C_0 \ldots C_{N-1})$.

Figure 3 illustrates complex interference coefficients $(C_0 \ldots C_{N-1})$ for typical values of frequency offset. In this particular example $\Delta fT = 0.2$ and $N = 16$, with phase-offset equal to zero at the beginning of the symbol period. The real components of the complex interference coefficients are represented by diamonds and the imaginary components are represented by triangles. ICI may be interpreted in terms of the complex interference coefficients $(C_0 \ldots C_{N-1})$ that give the contribution of each transmitter subcarrier to each demodulated subcarrier.

As may be seen from Figure 3, the complex interference coefficients $(C_0 \ldots C_{N-1})$ vary smoothly between subcarriers except, of course, for the transitions from the subcarrier that carries the data to be transmitted

to the adjacent subcarriers. This observed behāviour provides that embodiments of the present invention have substantially consistent performance under a variety of conditions.

It has been found that the form of this variation of complex interference coefficients ($C_0 \ldots C_{N-1}$) may be approximated by a relatively low order polynomial equation. This mathematical predictability is used to provide a reliable cancellation scheme in accordance with the embodiments of the present invention.

In typical prior art OFDM systems, ISI also causes ICI. In other words the delayed echo of one subcarrier causes interference not only in the subcarrier of the same frequency in the following symbol but in many other subcarriers of the following symbol as well. Polynomial cancellation properties designed to cancel ICI due to frequency offset also cause cancellation of the ICI due to ISI. In embodiments of the present invention, it is weighted groups of subcarriers rather than individual subcarriers that must be considered. Thus delayed echoes of one weighted group of subcarriers in one symbol cause interference only in a few summed and weighted outputs. These are the outputs corresponding to the group of subcarriers at the same frequency as the interfering signal and the groups immediately adjacent in frequency. This means that equalization to counter the effects of multipath transmission can be achieved with a relatively simple frequency domain equalizer.

An example of an embodiment of the present invention is now described in relation to Figures 4A and 5A for carrier systems. Corresponding Figures 4B and 5B are for equivalent baseband systems are provided for illustrative purposes but are not discussed.

The input data ($d_{0,i} \ldots d_{D-1,i}$) is provided on input data channels. The input data channels are then split into a number of weighted input data channels carrying weighted input data ($b_{0,i} \ldots b_{N-1,i}$) provided by the weighting means 1. In this case the weighting means 1 is constituted by the combination of the transmitter pre-weighting coefficients ($K_0 \ldots K_{D-1}$) and the transmitter weighting coefficients ($p_0 \ldots p_{W-1}$). Each input data ($d_{0,i} \ldots d_{D-1,i}$) on the input data channels is multiplied by a transmitter pre-weighting coefficient ($K_0 \ldots K_{D-1}$) and the transmitter weighting coefficients ($p_0 \ldots p_{W-1}$) in order to generate W weighted representations of the input data ($d_{0,i} \ldots d_{D-1,i}$). Collectively these weighted representations of the input data ($d_{0,i} \ldots d_{D-1,i}$) are termed weighted input data ($b_{0,i} \ldots b_{P-1,i}$).

The orthogonal transform 3 provides the orthogonality required for a MCM system. The number of inputs to the orthogonal transform N directly corresponds with the number of subcarriers N. Each output of the orthogonal transform 3 in the transmitter corresponds with a transmitter transform output data channel.

The transmitter transform output data ($c_{0,i} \ldots c_{N-1,i}$) are then input to the parallel-to-serial converter 7 in order to produce transmitter aggregate data s_k that is a linear sequence of values that is appropriate for transmission. The parallel-to-serial converter 7 produces transmitter aggregate data s_k on a transmitter aggregate data channel.

The transmitter aggregate data s_k is passed through a digital-to-analog converter 8 to produce a transmitter baseband signal $s(t)$. In practical MCM systems it is typical to introduce a guard interval between the symbols on the transmitter aggregate data channel.

The problem of intersymbol interference due to multipath echoes may be significantly reduced by the use of guard intervals between symbols. Use of guard intervals also helps to reduce ICI that may arise due to sampling errors at the receiver. When guard intervals are used, the guard interval should only be a small percentage of the symbol period in order to ensure acceptable bandwidth efficiency. Consequently the number of subcarriers must be sufficient to ensure that this is the case.

Thirdly, the performance of prior art systems is degraded over multipath channels. Embodiments of the present invention improve performance on multipath channels owing to a concentration of energy in the middle of the symbol period. As such, the use of cyclic prefixes can be reduced in length or eliminated entirely.

Low-pass filtering may also be included in the transmitter in order to improve the transmission characteristics of the analog transmission signal $u(t)$. In practical systems, a combination of analog and digital low pass filtering would typically be used, as is well known to persons skilled in the art. Analog low pass filtering may be included in the digital-to-analog converter 8 and digital low pass filtering may be included in the orthogonal transform 3. For example, digital low pass filtering in the orthogonal transform 3 may be achieved by using a higher order transform than is otherwise necessary. The input data ($d_{0,i} \ldots d_{D-1,i}$) is confined to the lower frequencies of the orthogonal transform 3 and the higher frequencies of the orthogonal transform 3 are supplied with zero inputs. Other and/or alternative techniques of providing low pass filtering may also be used by a person skilled in the art.

In baseband systems such as would be used over a public switched telephone network (e.g. ADSL and similar applications) the transmitter baseband signal $s(t)$ is the signal that is transmitted and this signal is, of course, real.

However, in carrier systems it is necessary to multiply the transmitter baseband signal $s(t)$ by a transmitter local carrier frequency signal $\exp(j2\pi f_c t)$ 9 in order to produce a signal that may be transmitted, termed the analog transmission signal $u(t)$. For example, a microwave or radio wave frequency may be used as a transmitter local carrier frequency signal $\exp(j2\pi f_c t)$ 9.

It is preferred to use a quadrature system in carrier systems whereby an inphase and quadrature carrier waveforms are transmitted. Hence the transmitter local carrier frequency signal $\exp(j2\pi f_c t)$ 9 is denoted as a complex exponential frequency signal.

In the receiver a converse operation occurs. In carrier systems, the incoming analog reception signal $v(t)$ is first multiplied by the receiver local carrier frequency signal $\exp(j2\pi f_r t)$ 10 in order to produce a receiver baseband signal $r(t)$. The receiver baseband signal $r(t)$ is then input to the analog-to-digital converter 11 in order to produce receiver aggregate data r_k. Low pass filtering may also be included as part of the analog-to-digital converter 11 and/or the orthogonal transform 16 as described in relation to the transmitter. For example, it is generally appropriate to low-pass filter the receiver baseband signal before analog-to-digital conversion to avoid aliasing effects.

The receiver aggregate data r_k is input to the serial-to-parallel converter 12 that produces receiver

transform input data $(x_{0,i} \ldots x_{N-1})$. The receiver transform input data $(x_{0,i} \ldots x_{N-1})$ is then input into an orthogonal transform 16 to produce weighted output data $(y_{0,i} \ldots y_{P-1,i})$. The weighted output data is then multiplied by receiver weighting coefficients $(q_0 \ldots q_{W-1})$ and then summed and multiplied by receiver post-weighting coefficients $(L_0 \ldots L_{D-1})$ to produce the output data $(e_{0,i} \ldots e_{D-1,i})$ that corresponds with the input data $(d_{0,i} \ldots d_{D-1,i})$ in the transmitter. In this case the receiver weighting coefficients $(q_0 \ldots q_{W-1})$ and the receiver post-weighting coefficients $(L_0 \ldots L_{D-1})$ together with the summing junctions corresponds to the weighting means 18 in the receiver.

The classes of embodiments of the present invention that are described below are characterised by the form of the mapping of the data to the weighted input data. All these classes of embodiments of the present invention may alternatively be realised in two other forms. The first form is the use of an orthogonal transform 3 and 16 with more inputs/outputs than are otherwise necessary (an 'oversized' orthogonal transform) and an exponential roll-off window 5 and 13. This is shown in Figures 17A and 17B.

The second form is the use of a 'normal-sized' orthogonal transforms 3 and 16, in combination with a cyclic extension 4 and cyclic contraction 14, as well as an exponential roll-off windows 5 and 13. This is shown in Figures 18A and 18B.

It is preferred that the exponential roll-off window 13 is the complex conjugate of the exponential roll-off window 5 so that the sign of the output data agrees with that of the input data. The cyclic contraction is preferably achieved by simply performing an element-by-element summation of the data points indexed $0 \ldots N/I-1$

with those data points indexed N/I ... $2N/I-1$ and so on up to $N(I-1)/I-1$ ... $N-1$. It is preferred that I is 2 in which case the number of data values is doubled and then halved by the cyclic extension 4 and cyclic contraction 14 respectively. In this case the data points indexed 0 ... $N/2-1$ are summed with data points indexed $N/2$ ... $N-1$ to provide N/2 data points for the receiver orthogonal transform. The value I may take values other than two, most conveniently higher powers of 2 such a 4, 8 etc.

Three general classes of embodiments of MCM systems will be described in which each input data ($d_{0,i}$ ... $d_{D-1,i}$) may be represented by an arbitrary number of weighted input data ($b_{0,i}$ ... $b_{P-1,i}$).

These three classes of embodiments are described in terms of a data transmitter. There is no need to additionally describe these embodiments in terms of a data receiver as the data receiver is determined from, and corresponds with, the data transmitter.

A first class of embodiments that represents a data transmitter for a carrier system may be described in relation to Figure 4A. In reference to Figure 4A, p_0, p_1 ... p_{W-1} are complex coefficients of the polynomial $(1-x)^{W-1}$ where $W > 1$, and $p_0 = 1$, p_1 is the coefficient of x, p_2 is the coefficient of x^2 and so on. The factors K_0 ... K_{D-1} are complex factors that allow changes in amplitude and phase.

Included in this first class of embodiments are those with transmitter weighting coefficients p_0, ... p_{W-1} as outlined below.

If transmitter weighting coefficients p_0 ... p_{W-1}

$$p_0 = 1,\ p_1 = -2,\ p_2 = 1$$

are used the corresponding receiver weighting

coefficients $q_0 \ldots q_{W-1}$ may be made equal to the transmitter weighting coefficients

$$q_0 = 1,\ q_1 = -2,\ q_2 = 1$$

Such an arrangement ensures that the receiver is an optimum receiver (in the matched filter sense) if it may be assumed that the noise is independent (ie white noise) with zero mean. This principle also applies to higher order cancellation schemes.

If transmitter weighting coefficients and receiver weighting coefficients are both such that

$$p_0 = 1,\ p_1 = -2,\ p_2 = 1$$
$$q_0 = 1,\ q_1 = -2,\ q_2 = 1$$

then the resulting data transmission and reception provides cancellation of the component of ICI that arises from the cubic variation of complex interference coefficients ($C_0 \ldots C_{N-1}$) with subcarrier index i. Such a system is considered to provide cubic cancellation. Similarly for higher order schemes as outlined below.

Quintic cancellation may be achieved with the following transmitter weighting coefficients and receiver weighting coefficients for $W = 4$.

$$p_0 = 1,\ p_1 = -3,\ p_2 = 3,\ p_3 = -1$$
$$q_0 = 1,\ q_1 = -3,\ q_2 = 3,\ q_3 = -1$$

This corresponds to the polynomial

$$1 - 3x + 3x^2 - x^3$$

7[th] order cancellation may be achieved with the following transmitter weighting coefficients and receiver weighting coefficients for $W = 5$.

$$p_0 = 1,\ p_1 = -4,\ p_2 = 6,\ p_3 = -4,\ p_4 = 1$$
$$q_0 = 1,\ q_1 = -4,\ q_2 = 6,\ q_3 = -4,\ q_4 = 1$$

This corresponds to the polynomial

$$1 - 4x + 6x^2 - 4x^3 + x^4$$

9th order cancellation may be achieved with the

following transmitter weighting coefficients and receiver weighting coefficients for $W = 6$.

$p_0 = 1,\ p_1 = -5,\ p_2 = 10,\ p_3 = -10,\ p_4 = 5,\ p_5 = -1$

$q_0 = 1,\ q_1 = -5,\ q_2 = 10,\ q_3 = -10,\ q_4 = 5,\ q_5 = -1$

This corresponds to the polynomial

$$1 - 5x + 10x^2 - 10x^3 + 5x^4 - x^5$$

11th order cancellation may be achieved with the following transmitter weighting coefficients and receiver weighting coefficients for $W = 7$.

$p_0 = 1,\ p_1 = -6,\ p_2 = 15,\ p_3 = -20,\ p_4 = 15, p_5 = -6, p_6 = 1$

$q_0 = 1,\ q_1 = -6,\ q_2 = 15,\ q_3 = -20,\ q_4 = 15, q_5 = -6, q_6 = 1$

This corresponds to the polynomial

$$1 - 6x + 15x^2 - 20x^3 + 15x^4 - 6x^5 + x^6$$

Coefficients for embodiments incorporating higher order cancellation are similarly simply derived from the polynomial $(1-x)^{W-1}$.

The coefficients may be provided by expanding this polynomial, or by reference to a Pascal triangle:

```
                1
             1  -2  1
          1  -3   3  -1
        1  -4   6  -4   1
     1  -5  10  -10  5  -1
   1  -6  15  -20  15  -6  1
 1  -7  21  -35  35  -21  7  -1
1  -8  28  -56  70  -56  28  -8  1
```

The values of $K_0 \ldots K_{D-1}$ may be left unspecified. Modifying amplitude and phase by modifying $K_0 \ldots K_{D-1}$ may be desirable for any number of reasons. For instance, it may be necessary to adjust the amplitude of certain channels to equalize the signal. It may be necessary to adjust the phase of the signal to modify the power characteristics of the signal.

A second class of embodiments may also be described in relation to Figure 4A which is a schematic diagram of an example of an MCM transmitter according to an embodiment of the present invention.

The transmitter weighting coefficients $p_0, \ldots p_{W-1}$ are coefficients of the polynomial

$$(1-x)(1+g_1x+g_2x^2+\ldots g_{W-2}x^{W-2})$$

where $p_0 = 1$, p_1 is the coefficient of x, p_2 is the coefficient of x^2 etc. In many embodiments the expression

$$(1+ g_1x + g_2x^2 + \ldots g_{W-1}x^{W-1})$$

will also have $(1-x)$ as a factor.

The complex values of g_0, g_1, g_2, g_3 etc. may be chosen to optimise other characteristics of the transmission such as the peak-to-mean transmitted power.

The first class of embodiments is a subset of the second class of embodiments.

A third class of embodiments may be described in relation to Figure 6A which is a schematic diagram of part of an example of an MCM transmitter with a generalised mapping between input data $(d_{0,i} \ldots d_{D-1,i})$ and weighted input data $(b_{0,i} \ldots b_{P-1,i})$.

In this third class of embodiments, ICI cancellation is achieved in the transmitter so that the individual decoded weighted output data $(y_{0,i} \ldots y_{P-1,i})$ in the receiver is relatively free of ICI and is used to estimate the input data $(d_{0,i} \ldots d_{D-1,i})$.

In this case the $(K_0, \ldots K_{D-1})$ and $(p_0 \ldots p_{W-1})$ notation is not directly applicable as the possible mappings cannot be calculated simply by multiplying the input data $(d_{0,i} \ldots d_{D-1,i})$ by weighting factors.

This may be done by two alternate methods.

In a first method, the mapping of the input data $(d_{0,i} \ldots d_{D-1,i})$ onto weighted input data $(b_{0,i} \ldots b_{P-1,i})$ is fixed and does not change from symbol period to symbol period. In other words there is a simple mapping from the x possible values that the input data d might have (typically but not exclusively this would be a power of 2, ie 2, 4, 8, 16 etc) to x combinations chosen from the possible values of $(K_0, \ldots K_{D-1})$ that are chosen to fit some particular criterion - eg maximum Euclidean distance to minimise BER or some combination of limitation of power roll-off, insensitivity to frequency offset, minimise peak-to-mean power ratio.

In a second method, the mappings may change from symbol period to symbol period in a predetermined way to implement codes similar to trellis code modulation. Typically $2x$ combinations of Ks would be defined but only x would be allowable in any particular symbol period.

As an example consider the case of grouping in fours in the transmitter.

There are many ways that this could be achieved.
To achieve linear cancellation with four carriers, the carriers must be weighted with the coefficients of

$$(1-x)^2(g_0+g_1x)$$

where g_0 and g_1 are any values including complex values. Different values of input data can be mapped to

different combinations of g_0 and g_1. For example, g_0 and g_1 could be allowed to take values 1+j, 1-j, -1+j, -1-j. Then there are sixteen possible combinations and 4 bits could be mapped onto the four carriers.

At the receiver y_0 is used as an estimate of g_0 and $-y_3$ is used as an estimate of g_1. The linear component of ICI is cancelled in each of these values. However, the performance with respect to noise is not optimal due to the asymmetry between transmitter and receiver and the consequent breakdown of the matched filter condition.

The above described embodiments have a reduced effective data rate as the number of independent signals that are modulated is reduced by a factor of two, three or more depending on the particular code used. However, according to other embodiments of the present invention, techniques may be used to increase the effective data rate. These embodiments allow the effective data rate to be increased from what it would otherwise be without overlapping transmission.

Overlapping transmission can be provided in the time domain and/or the frequency domain. Some if not all of the other advantages of polynomial weighting are retained in these embodiments.

Overlapping transmission of symbols in the time domain is dealt with firstly. Figure 7 represents an embodiment in which sample values from adjacent overlapping symbols are overlapped in the time domain. In the transmitter, symbols are overlapped in the time domain by selectively delaying groups of transmitter delay data output from the orthogonal transform 3 so that the transmitter aggregate data which is ultimately transmitted consists symbols that are overlapping in the time domain. The transmitter delay data are preferably adjacent sets of

transmitter transform output data with an equal number of members in each set, though it is not necessary that the sets be adjacent or have an equal number of members.

Figures 8A and 8B show general schematic diagrams of embodiments that incorporate overlapping transmission in the time domain. A general weighting means 1 is shown, though this could also be simple polynomial weighting or a overlapping coding as described below and represented in Figures 13.

In Figures 8, for example, symbols could be transmitted every T/2 instead of T, even though the actual symbol period is T. Here N might be 256 and m would be 128. Half of the $c_{0,i}$ ... $c_{N-1,i}$ are directly fed to the parallel-to-serial converter 7 while the other half are delayed for half a symbol period and are fed to the parallel-to-serial converter 7. However, the actual value of the overlap is not constrained - it could be more, or less, than T/2.

Figure 8C represents part of an embodiment in which there is a general overlap of N-m symbols between adjacent symbols. A new symbol begins transmission every mT/N seconds. Accordingly only the first m samples of each symbol do not overlap with the following symbol.

The delay means 6 and parallel-to-serial converter 7 can be considered as a number of delay elements 6.2 ... 6.N/m and parallel-to-serial converter elements 7.1 ... 7.N/m.

The delay means 6 is connected with the parallel-to-serial converter 7 as indicated in Figure 8C. Transmitter delay data output from a delay element 6.x which are passed through a corresponding parallel-to-serial converter 7.x provide the transmitter aggregate

data. Each parallel-to-serial converter element 7.x outputs a value every T/N seconds. Thus, owing to the delay stage 6, symbols are transmitted more frequently than every T seconds, even though the symbol period is T.

Each delay element has a different delay time. Successive delay elements 6.2 ... 6.N/m will have a delay of T(m/N), T(2m/N), T(3m/N) through to T(N-m)/N. Each parallel-to-serial converter element has a single output each time interval of T/N. These are summed as shown to provide the output of the parallel-to-serial converter 7.

Figures 9A and 9B show the corresponding receivers to those of Figures 8A and 8B. A delay means 15 is used to provide the orthogonal transform 16 with different combinations of receiver delay data so that the output data can be subsequently estimated using the estimation means 17. This is represented in Figure 9C.

Figure 9C shows a variable delay means 15A selectively delays groups of receiver delay data by differing amounts so that appropriate combinations of receiver delay can be serially passed into the N-stage shift register 15B at a rate of one value every T/N. The N-stage shift register 15B synchronises the release of each set of N outputs $x_{0,i}$ ... $x_{N-1,i}$ at a rate of mT/N. The orthogonal transform 16 transforms the N parallel outputs from the N-stage shift register 15B each mT/N.

In the case of distortion free transmission, the group of N values used as input to the orthogonal transform 16 include all the samples depending on one transmitted symbol (refer Figure 7). For the case where the received signal is a distorted noisy representation of the transmitted signal, symbol synchronisation is used to

adjust the delay of the serial data to minimise the overall bit error rate of the system.

Increasing the overlap increases the data rate but also increases the complexity of the receiver and increases the effect of added noise in the transmission channel. Overlapping in the time domain also improves the distribution of instantaneous signal amplitudes in the transmitted signal.

It might be inferred from the above description of a transmitter and receiver incorporating overlapping transmission in the time domain that *m* must be a factor of N but this is not the case. If *m* is not a factor of N then the last delay stage has fewer than *m* inputs.

In embodiments in which a receiver incorporated overlapping transmission in the time domain, a different estimation means 17 is required compared with other embodiments. Figures 10 and 11 show an estimation means 17 used to estimate the output data when a delay means 15 is included. Such an estimation means 17 is appropriate for embodiments represented in Figures 8A and 8B.

The transmitted data is retrieved from the overlapped symbols using an equalizer 17D in the frequency domain. That is, the equalizer 17D is after the DFT in the receiver not before it. The equalizer 17D operates on the weighted sums of the outputs of the orthogonal transform 16.

The equalizer 17D is made up of a number of equalizer elements 17D as shown in Figure 11. Feature 17A is a block that provides for weighting and summing of the receiver transform output data substantially as described earlier in relation to embodiments of the

invention that do not include overlapping transmission of symbols in the time domain. Subsequent blocks 17B and 17C are simple delay blocks that delay data uniformly by a period of mT/N. These blocks are included to provide each equalizer element 17D with all the values necessary to estimate a particular output data at any given time.

More complicated linear equalization schemes may be appropriate if multipath transmission is a particular problem or if there is overlap in the time domain greater than T/2. such that a given sample depends significantly on more data points than those terms included as input to the described equalizer element 17D.

Use of an equalizer 17D in the receiver causes very little noise enhancement as signal energy is concentrated in the middle of the symbol period. The equalizer 17D has only a few significant terms because the polynomial cancellation properties of described embodiments result in only a few interfering terms being significant.

There are a number of different types of equalizers that are commonly used in data communications: linear equalizers, decision feedback equalizers and maximum-likelihood sequence estimators. While decision feedback equalizers and maximum-likelihood sequence estimators can be used with certain embodiments, the most generally applicable in this case is the linear equalizer as shown in Figure 11. The main disadvantage of linear equalization is noise enhancement. The signal to noise ratio after equalization is less than before equalization. However in this case, because the power in the weighted sums of the outputs of the DFT due to the unwanted overlapping signal from the previous and following symbol periods is so much smaller than the

power of the wanted signal, noise enhancement is not overly significant and in many cases is negligible. (For example for coding in pairs and an overlap of T/2 the unwanted power is about 12dB below the wanted power and the noise power would be enhanced by the order of 1%).

The complexity of the equalizer 17D depends on how many significant terms there are to be cancelled out. In embodiments of the present invention, ICI due to ISI is limited to the weighted group of subcarriers causing the interference and the few groups on either side. In most cases it is likely that only one group on either side will be significant, so that a nine tap equalizer would be required for each group of subcarriers. This consists of three taps for the preceding symbol, three taps for the current symbol (three not one, so that the effect of delayed versions of the current symbol due to echoes are also equalized) and three for the following symbol. This is the configuration of equalizer element 17D shown in Figure 11. to achieve an instance of the output data $e_{k,i}$, an estimate of the input data $d_{k,i}$. Corresponding equalizer elements are required for other data, with slightly modified equalizer elements appropriate for estimating end data such as $e_{0,i}$ and $e_{N,i}$.

For the case of coding onto pairs of subcarriers and with symbols being transmitted at rate T/2 this would mean that the number of computations per time T would be N/2 * 9 *2.

This is because there are N/2 equalizer outputs in every symbol. Each output requires the computation of 9 significant terms. The symbols arrive at rate 2/T.

This compares favourably with the time domain equalizers that have been proposed for typical prior art OFDM systems. For a time domain equalizer, calculations are

required for each time domain sample ie N times per symbol. To have comparable complexity only 9 time domain terms could be equalized. As the delayed echoes are likely to last for much more than 9 time domain samples, the overall complexity of the frequency domain equalizers will be much less than time domain equalizers proposed for typical prior art OFDM systems.

The effective data rate can be also be increased by overlapping symbol data in the frequency domain. There are a number of methods which can be used. One method is comparable to partial response signalling, with a more general method using CDMA techniques.

A particular technique for achieving overlapping transmission in the frequency domain in a manner comparable to partial response signalling is now described.

The weighting means 1 of other embodiments can be replaced with a coding means 2 in the transmitter. The coding means 2 provides a mapping between the input data ($d_{0,i}...d_{D-1,i}$) and the coded data ($b_{0,i}...b_{N-1,i}$). This is illustrated in Figures 12A and 12B.

The input data ($d_{0,i}$ ... $d_{D-1,i}$) are received by the coding means 2 that maps the input data ($d_{0,i}$ ... $d_{D-1,i}$) into coded data ($b_{0,i}...b_{N-1,i}$). The mapping provided by the coding means 2 may be simple collocation whereby the coding means 2 provides one-to-one mapping between the representations of the input data ($d_{0,i}$ ... $d_{D-1,i}$) and the coded data ($b_{0,i}...b_{N-1,i}$). In such embodiments the coding means 2 is effectively identical with some embodiments of the weighting means. However, in other embodiments the coding means 2 provides an arithmetic coding of the weighted input data in which each coded data ($b_{0,i}...b_{N-1,i}$) depends on one or more of the input data ($d_{0,i}$ ... d_{D-}

$_{1,i}$).

The coded data ($b_{0,i} \ldots b_{N-1,i}$) is input into an orthogonal transform 3 that transforms the coded data ($b_{0,i} \ldots b_{N-1,i}$) into transmitter transform output data ($c_{0,i} \ldots c_{N-1,i}$).

In some embodiments, the coding means 2 essentially ensures that the input data ($d_{0,i} \ldots d_{D-1,i}$) are modulated onto overlapping groups of subcarriers. In preferred embodiments, the difference between adjacent weighted input data is taken to produce coded data. This addresses one particular problem with the system disclosed by Zhaö and Haggman, namely a reduction in data rate which follows from the use two subcarriers to carry representations of the same input data.

Figures 12C and 12D show the corresponding receivers. The receivers are similar to those shown in Figures 5A and 5B in relation to other embodiments of the present invention. However, the weighting means 18 is replaced with estimator means 17 to estimate the output data in these embodiments. The function of the estimator means 17 may be achieved by various methods as is known to a person skilled in the art. Any number of sequence estimation techniques relying on correlations between samples may be used to optimally estimate the output data. Such techniques are appropriate as sample-by-sample decoding will not provide adequate performance under all circumstances. It is preferred that the estimator means 17 use some form of maximum likelihood decoding to achieve better performance.

Various schemes are possible for the coding means 2 in the transmitter. Figure 13A shows one such configuration for the case where each coded data depends on more than one input data. Adjacent input data are differenced to provide an input to the orthogonal transform. In this

particular embodiment, each input to the orthogonal transform consists of the difference between adjacent input data samples.

Figure 13B illustrates a similar example but with each coded data depending on three input data.

Note that in Figure 13A and 13B, the coding means 2 "wraps around" the end points.

In Figure 13B, in which input data is grouped in threes, rather than twos as for Figure 13A there will necessarily be a greater number of values the coded data can take. In the case of binary data for Figure 13B, the coded data will take values {-4, -2, 0, 2, 4,}.

More generally, an increasing amount of "overlap" (that is, having coded data depend on an increasing number of input data) increases the number of symbol levels the coded data will be spread across. Thus, for embodiments of greater "overlap", noise immunity will be reduced if the decoding is restricted to estimating each value of $e_{0,1} \ldots e_{D-1}$ independently. However, this loss in noise immunity can be largely offset by using maximum likelihood decoding, despite the inherent complexity in considering a large number of possible bit sequences.

Figure 13D illustrates an alternate embodiment where the coding means 2 provides a mapping of input data to coded data where each input data maps to three weighted input data, but with each depending at most on two input data. Such an embodiment reduces the data rate but provides the possibility of using very simple receiver that only considers subcarriers depending on a single input data.

For the embodiments illustrated in Figures 13A to 13D where the coding means may provide coded data depending

on more than one input data, equivalent windowing embodiments using cyclic extensions are possible. These rely on a linearity property of the orthogonal transform. Embodiments where coded data depends on more than one input data may be alternatively realized by summing the output of the orthogonal transform for the input data on which coded data depends. That is, the coding means 2 may essentially be alternatively provided after rather than before the orthogonal transform. Performing the orthogonal transform before the coding means allows the orthogonal transform to be replaced by a number of parallel lower-point orthogonal transforms followed by cyclic extensions and a complex windowing operation. The complex window will generally be different for each parallel path. While alternative windowing embodiments of embodiments incorporating overlapping transmission are possible, their use provides little advantage over simpler weighting embodiments. These alternative embodiments are within the scope of the present invention.

The configuration of the coding means 2 in Figure 13A may be considered as a 1-D code, in analogy with the well known technique of partial response signalling code. With partial response signalling, data is mapped onto overlapping groups of symbols in the time domain. However, in the present invention, input data to be transmitted is transformed onto overlapping groups of subcarriers in the discrete frequency domain.

With partial response signalling, a 1+D code is required is reduce sensitivity to timing errors. However, it is found that in relation to the present invention, a coding means that may be referred to as 1-D is preferred for reducing the sensitivity to frequency errors; that is, the subcarriers code the difference between data symbols.

It is noted that despite the comparisons that may be made between the frequency-domain approach of the present invention and the known time-domain techniques of partial response signalling, there has hitherto been no application of the known techniques to the problems that the present invention attempts to address.

There is a significant body of literature separately dealing with OFDM systems and partial response signalling, but no previous publications dealing with the application of partial response signalling to OFDM systems in particular or MCM systems in general. One possible explanation is that the literature dealing with OFDM systems simplifies the spectra of OFDM subcarriers and does not illustrate the alternating polarities of those subcarriers. Another misconception present in the literature dealing with OFDM systems is the explanation of intercarrier interference. The literature explains that each subcarrier has a continuous spectra that has a null at the centre frequencies of other subcarriers; frequency offset disturbs these nulls which accordingly results in intercarrier interference. However, this is not correct as it is the breakdown in orthogonality of the complete spectra of each subcarrier due to frequency offset that causes intercarrier interference.

Despite some comparisons that may be drawn between the teaching of the present invention, and the techniques involved in partial response signalling, there are also significant differences. Foremost is the fact that partial response signalling is a continuous process while the techniques described herein are performed on a limited number of subcarriers. However, there exist techniques associated with partial response signalling (such as trellis coding, and enhanced decoding techniques for partial response signals) that are

equally applicable to the present invention without departing from the scope of the present invention.

In embodiments of the present invention, weighting coefficients in the weighting means or coding means may be chosen to optimise characteristics such as the peak-to-mean transmitted power. In this respect a person skilled in the art may make use of the teachings presented in a paper by Wilkinson and Jones ("Minimisation of the Peak to Mean envelope Power Ratio of Multicarrier Transmission Schemes by Block Coding", *IEEE 45th Vehicular Technology Conference*, Chicago, 1995, pp.825-829), wherein it is discussed how coding may be used to reduce peak-to-mean power in conventional OFDM systems.

Other schemes to reduce the impact of peak-to-mean power are also possible. In particular, it is possible to consider phase-offsetting subcarriers to reduce peak-to-mean power. For example, certain subcarriers may have subcarrier frequency signals that are phase offset from other subcarrier frequency signals to a predetermined extent. A variety of schemes are possible and are within the scope of the present invention.

While the data rate can be increased by overlapping in the frequency domain, in a manner analogous to partial response signalling, and a more general method using CDMA may alternatively be used.

The distinction between these methods is best explained by examples. To simply the examples, only real data values are considered though the examples can be readily extended to complex data. Suppose the data to be transmitted is 0110 and an embodiment with mapping onto two subcarriers is to be used. The eight subcarriers used to carry this data would have relative weightings:

-1 +1   +1 -1   +1 -1   -1 +1

The first 0 is carried by the first and second subcarriers which have relative weighting -1 and +1, the first 1 is carried by the third and fourth subcarrier which have relative weightings +1 -1 and so on.

If instead the form of frequency domain overlapping comparable to partial-response signalling is used then the data would be mapped onto the first five subcarriers.

-1+1	component of 1^{st} & 2^{nd} subcarriers due to 0
+1-1	component of 2^{nd} & 3^{rd} subcarriers due to 1
+1-1	component of 3^{rd} & 4^{th} subcarriers due to 1
-1+1	component of 4^{th} & 5^{th} subcarriers due to 0
-1+2 0-2+1	total component of subcarriers due to 0110

Thus for large N approximately the same number of bits can be carried as by normal OFDM.

Another way of looking at the signal above is as the sum of two signals that have boundaries between groups of subcarriers at different positions.

-1+1+1-1	boundaries between subcarrier 2 & 3 etc
+1-1+1-1	boundaries between subcarrier 1 & 2, 3 & 4

More general systems can be considered which are the sum of signals but with differing boundaries between groups of subcarriers.

CDMA methods could be used in which the signal used to transmit a 1 between two users was, for example:

+1 -1 +1 -2 +1 -1 +1

Note that different sizes of weighted groups can be used in one transmission. In this case the signal is spread in bandwidth by a factor of seven. This transmission has a group of two, followed by a group of three and a group of two. The signal to transmit a 1 between two other users is:

+1 -2 +1 +1 -1 +1 -1

Then a receiver which received the sum of these signals and wanted to extract the first message would correlate the signal with:

+1 -1 +1 -2 +1 -1 +1

A particular implementation of the above outlined principles for a frequency overlapping system comparable to partial-response signalling.

Each transmission retains the desirable properties of other embodiments: it has sharp roll-off in frequency and the power is concentrated in the centre of the symbol period. The sensitivity to frequency offset is also retained. As there is weighting in both transmitter and receiver and the weighting is over a minimum of two subcarriers, the sensitivity to frequency offset is equal or better than that achieved by linear cancellation in embodiments of the present invention.

In some systems, for example mobile telephone systems, the transmitter at the base station would be transmitting the sum of a number of these type of signals.

To be applied in a CDMA situation, it is necessary to accommodate the requirements of auto and cross correlation techniques required for CDMA codes. If the coded signal is to be directly mapped onto subcarriers, this means that CDMA codes that are compatible with embodiments of the present invention are necessary.

Prior art OFDM systems that incorporate CDMA techniques typically use interleavers between the coding and the mapping onto subcarriers. Embodiments of the present invention however, involve a combination of coding and the interleaving.

Returning to embodiments including a weighting means 1 as described above, it is also possible to provide embodiments with unequal numbers of weighting coefficients between the transmitter and receiver. An example of embodiments of such systems are illustrated in Figures 14A and 14B. There are some cases where such embodiments might be desirable. For example, if there is some relevant asymmetry between the transmitter and receiver.

In Figure 14A more transmitter subcarrier data channels are associated with each input data channel than receiver subcarrier channels associated with each output data channel. As an example, if transmitter weighting coefficients are

$$p_0 = 1,\ p_1 = -3,\ p_2 = 3,\ p_3 = -1$$

then a straightforward selection of appropriate receiver weighting coefficients may be

$$q_0 = 1,\ q_1 = -1$$

with

$$(L_0 \ldots L_{D-1}) = (K_0 \ldots K_{D-1})/6$$

In Figure 14B the converse arrangement is illustrated. More receiver subcarrier data channels are associated

with each output data than transmitter subcarrier data channels are associated with each input data channel. This arrangement is only partially illustrated in Figure 14B. In addition to generating $e_{1,i}$ and $e_{D-2,i}$ from $\{z_{1,i}, z_{2,i}, z_{3,i}, z_{4,i}\}$ and $\{z_{P-5,i}, z_{P-4,i}, z_{P-3,i}, z_{P-2,i}\}$ respectively, as illustrated, it is appropriate to use some of these weighted output data to also generate other output data. For instance, $e_{2,i}$ could be generated by using weighted output data $\{z_{3,i}, z_{4,i}, z_{5,i}, z_{6,i}\}$ and similarly for other output data.

Neglecting end effects, an embodiment may have transmitter and receiver weighting coefficients such that

$$p_0 = 1,\ p_1 = -1$$

and

$$q_0 = 1,\ q_1 = -3,\ q_2 = 3,\ q_3 = -1$$

with

$$(L_0 \ldots L_{D-1}) = (K_0 \ldots K_{D-1})/6$$

Endpoint output data $e_{0,i}$ and $e_{D-1,i}$ would be generated from a smaller set of weighted output data points (such as $\{y_{0,i}, y_{1,i}\}$ and $\{y_{5,i}, y_{6,i}\}$ respectively) and with modified receiver weighting coefficients as appropriate. Alternatively, it may be appropriate to use a cyclical arrangement in relation to endpoint output data such that it is not necessary to use a smaller set of weighted output data points to generate output data.

For most embodiments, however, it will be preferred that there are equal weightings in the transmitter and the receiver. This is because equal weightings in the transmitter and the receiver provides optimum noise performance when the noise may be assumed to be white noise with a flat power spectrum and zero mean. When this is not the case, it is likely that the best

practical solution is still to have equal weightings in the transmitter and receiver for the sake of simplicity. Similarly, it is preferred that embodiments that use windowing methods use windows that are complex conjugates of each other in the transmitter and receiver respectively.

Other embodiments of the present invention are also possible. Embodiments may be contemplated whereby there are a relatively large number of weighted input data channels are provided near the frequency boundaries of the MCM signal while a relatively few weighted input data channels are provided within the central portion of the MCM signal. Such an embodiment would provide a rapid power roll-off at the boundaries of the MCM signal while not compromising bandwidth efficiency by the use of unnecessary additional weighted input data channels in the central portion of the MCM signal. A schematic diagram example of embodiments of this type is illustrated in Figure 15.

Furthermore, some embodiments might not even use all of the subcarriers.

Other embodiments are also possible where the adjacent weighted input data channels do not correspond with adjacent input data channels. Such embodiments may be adopted in a number of situations where it might be desirable to do so. Typically though performance would not be improved in most transmission environments as the complex interference coefficients (as presented in Figure 3) would not vary as smoothly. However, if modifications of this sort are required, they are of a routine nature and may be carried out by a person skilled in the art. A schematic diagram example of embodiments of this type is illustrated in Figure 16.

More complicated combinations of the above types of modifications may also be contemplated by a person skilled in the art. In this respect there are a multitude of configurations that could be used. Slight variations may be preferred depending on the particular application, expected transmission conditions and specific performance goals, cost considerations and available bandwidth.

Embodiments using weighted input data may alternatively be achieved by using complex exponential windowing techniques.

Consider the simple case of cancelling in pairs: $a_{k+1} = -a_k$ where k is an even number.

An equivalent time domain windowing can be achieved by using a complex exponential window 5 given by $[1 - \exp(j2\pi l/N)]$ where input data $(d_{0,i} \ldots d_{D-1,i})$ to the orthogonal transform 3 is separated by two zero inputs. This is demonstrated in Figure 17A.

This may be alternatively realised using an $N/2$ point orthogonal transform 3 that provides a cyclic extension 4 of $N/2$ points and where the complex window 5 is given by $[1 - \exp(j2\pi l/N)]$. This is demonstrated in Figure 18A. A corresponding receiver using windowing methods would use a complex conjugate window.

Figures 17A and 18A relate to carrier systems. Corresponding Figures 17B and 18B are for equivalent baseband systems and are provided for illustrative purposes but are not discussed.

Windowing techniques per se are known in the prior art. Of the windows previously described in the literature, only the cosine roll-off window, satisfies the

orthogonality condition. The most effective previously known windowing method for reducing the effects of ICI due to frequency offset is a cosine roll-off window with roll-off factor of 1. This windowing has similar performance with respect to ICI as elementary embodiments of the present invention but has worse performance with respect to noise added in the channel.

The cosine roll-off windows previously described in the literature may be alternatively realised with weighting techniques. The known cosine roll-off windowing methods are equivalent to a weighting method which is not contemplated by embodiments of the present invention.

Figures 19 to 23 provide various performance graphs of embodiments of the present invention in contrast with the performance of comparable prior art systems.

Figure 19 is a scatterplot of symbols received in a system having frequency offset for a typical prior art OFDM system with 64 subcarriers.

Figure 20 is a scatterplot of symbols received in a system having frequency offset for an embodiment of the present invention that uses 64 subcarriers and linear cancellation.

Figure 21 is a scatterplot of symbols received in a system having frequency offset for an embodiment of the present invention that uses 64 subcarriers and cubic cancellation.

Figure 22 is a graph showing the signal to ICI noise ratio of an embodiment of the present invention compared with the signal to ICI noise ratio of a typical prior art OFDM system.

Figure 23A is a graph showing the power spectrum roll-off of a typical prior art OFDM system.

Figure 23B is a graph showing the power spectrum roll-off of an embodiment of the present invention.

MCM systems may use various different schemes to modulate subcarriers, such as PSK or QAM. Embodiments of the present invention do not depend on the mapping of data to be transmitted to input data ($d_{0,i} \ldots d_{D-1,i}$) and are therefore applicable to forms of modulation that can be used with MCM generally.

In many systems, data is mapped onto input data consisting of symbol constellations according to a PSK or QAM modulation system. There is a significant body of literature describing how data is mapped onto symbol constellations, such as by the use of Gray codes. Other techniques such as trellis code modulation and coded modulation may also be used. With coded modulation not all of the possible symbol constellation points that may be used in each symbol period. Instead there is a trellis of allowable constellation points at different symbol periods. All of these known techniques are compatible with embodiments of the present invention. Use of such known techniques in combination with the present invention is within the scope of the present invention.

It is preferred that the orthogonal transform used in embodiments of the present invention be a Fourier-based frequency transform, such as a DFT, DCT or DST. However, it is not necessary that the orthogonal transform be of this type as there are a number of other orthogonal transforms that may also be suitable, such as the Walsh transform, the Hadarmard transform and the many families of wavelet transforms as are known to those skilled in

the art.

The orthogonal transform means according to certain embodiments of the present invention may make use of fact that certain weighted input data channels are perfectly correlated as they differ only by a real factor that is the ratio of their respective complex weighting coefficients. This allows the use of certain techniques whereby the computational complexity of the orthogonal transform is reduced to a level approaching that the number of input data channels.

Though many of the aspects of the various embodiments are discussed solely in relation to an MCM or OFDM transmitter, it is understood that they apply equally to an MCM or OFDM receiver. Furthermore, these aspects of the various embodiments are not confined to wireless transmission systems but also apply to wired systems.

Further to the above embodiments, there are a variety of MCM systems that are not limited to a single transmitter and a single receiver. A number of MCM transmitters may be provided to provide a broadcast coverage of an MCM signal. Similarly, a number of MCM receivers may be provided for multiple users. In such broadcast systems there are also known to be systems whereby different transmitters and receivers may be assigned to different subsets of subcarriers. Some of these ideas are outlined in a recent paper by A.C. Caswell ("Multicarrier Transmission in a Mobile Radio Channel", *Electronic Letters*, 10th October 1996 Vol 32 pp. 1962-1963).

It is understood that the above described embodiments of the present invention do not limit the scope of the present invention but are indicative of the nature of the present invention. Many modifications may be made to the foregoing embodiments as would be known to a person

skilled in the art. The scope of the present invention extends to all such modifications as would be clear to a person skilled in the relevant art.

Dated this 22nd day of June 1998

LA TROBE UNIVERSITY

By their Patent Attorneys

GRIFFITH HACK

Fellows Institute of Patent

Attorneys of Australia

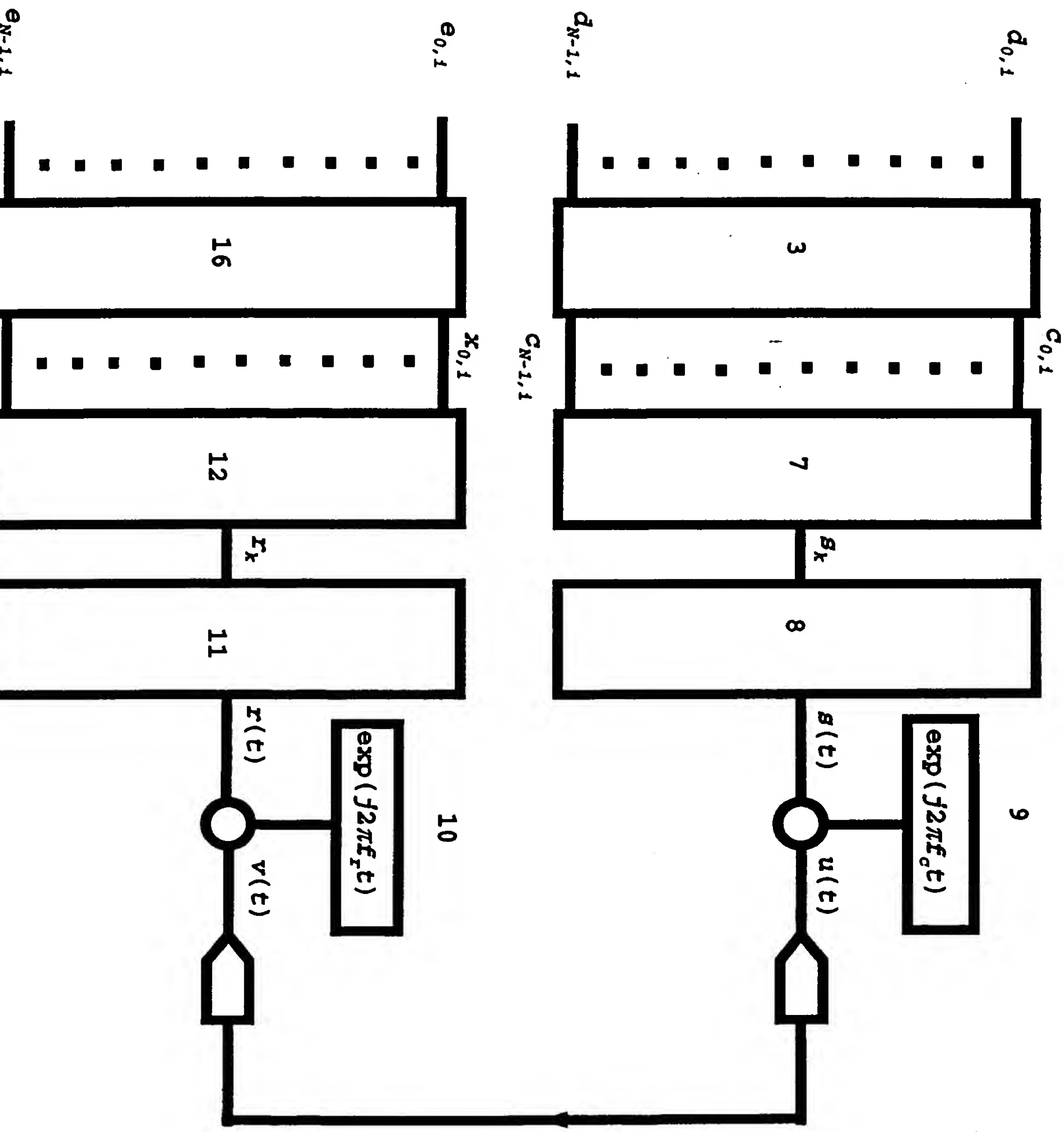

$d_{0,1}$
$d_{N-1,1}$
3
$c_{0,1}$
$c_{N-1,1}$
7
s_k
8
$s(t)$
$\exp(j2\pi f_c t)$
9
$u(t)$
$e_{0,1}$
$e_{N-1,1}$
16
$x_{0,1}$
$x_{N-1,1}$
12
r_k
11
$r(t)$
$\exp(j2\pi f_r t)$
10
$v(t)$

FIGURE 1

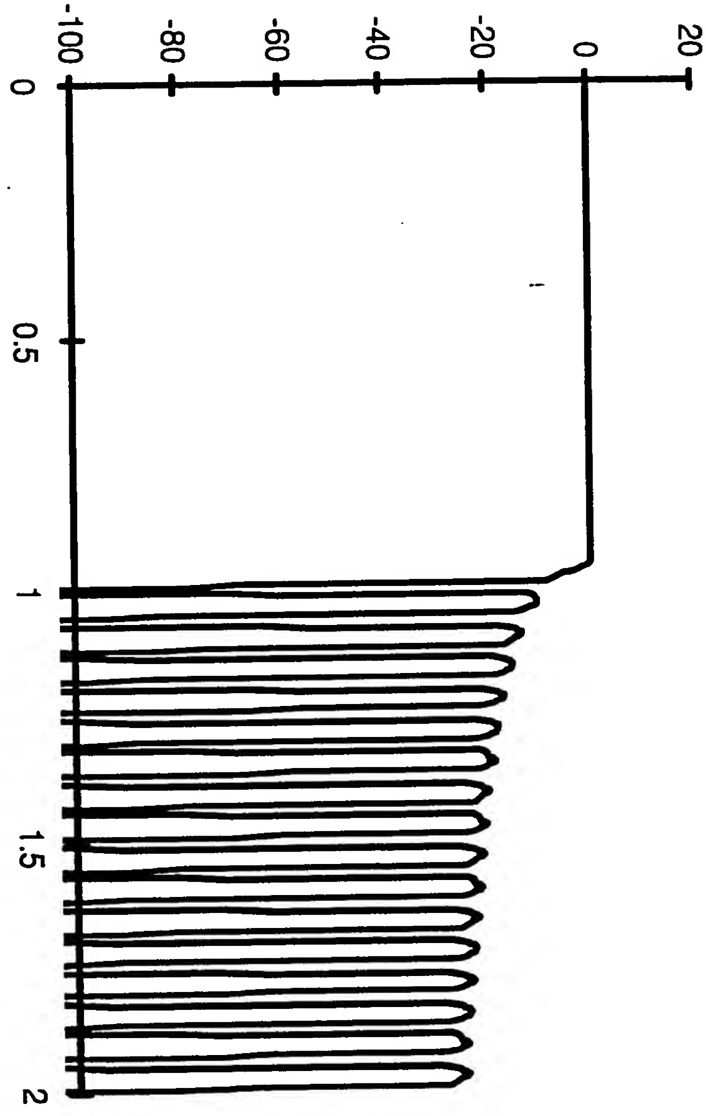


FIGURE 2

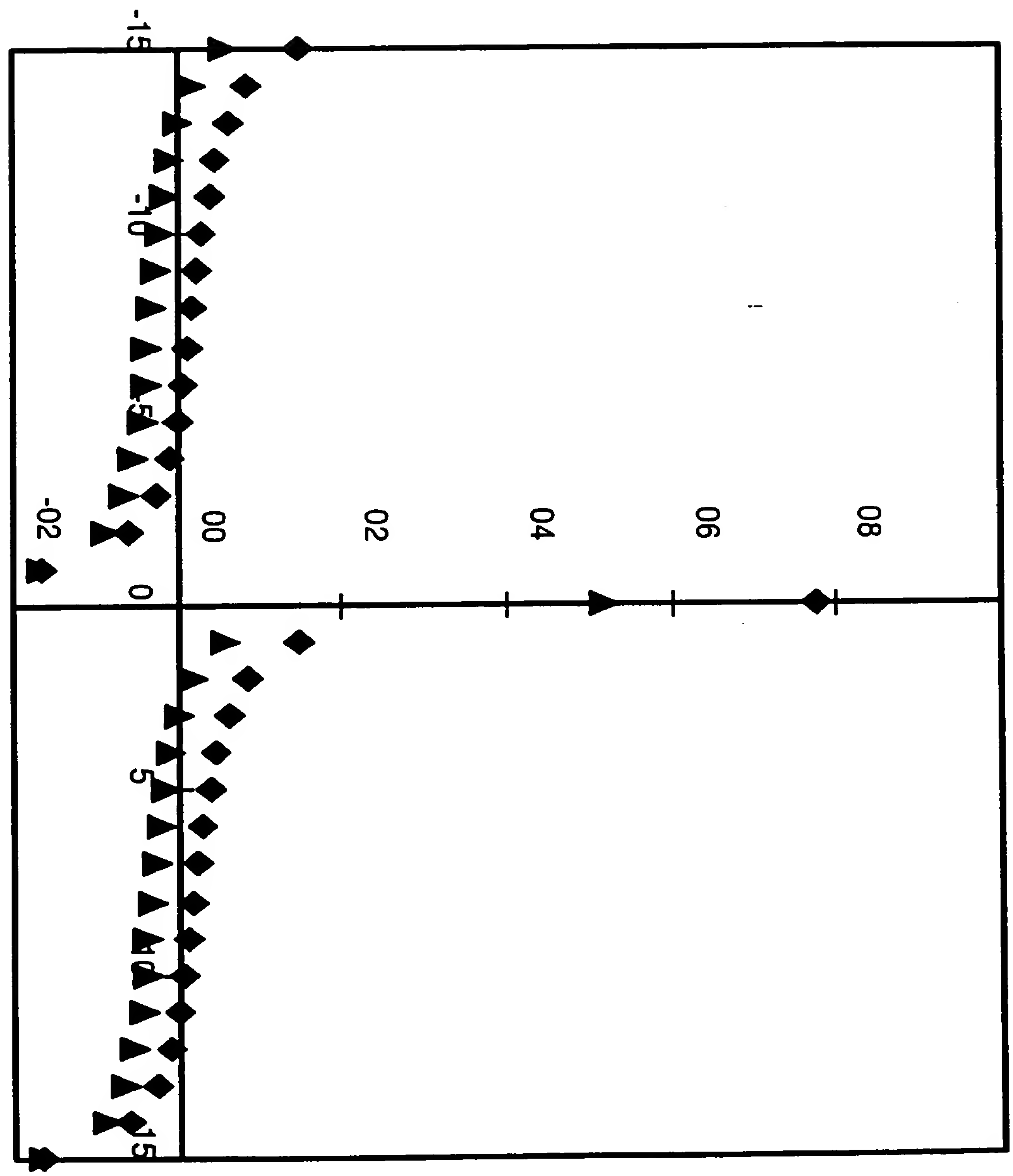


FIGURE 3

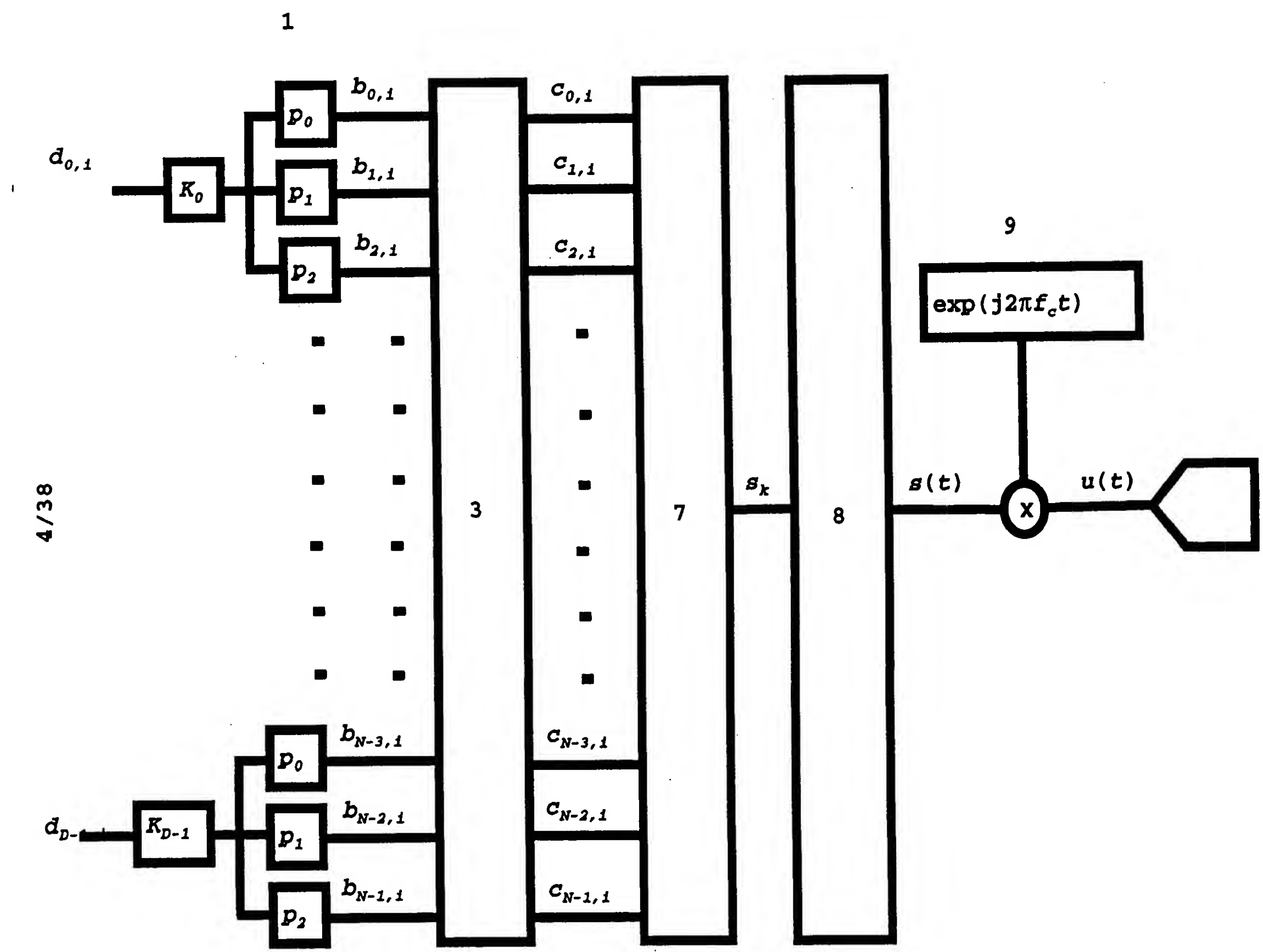

1
$d_{0,i}$
K_0
p_0
p_1
p_2
$b_{0,i}$
$b_{1,i}$
$b_{2,i}$
d_{D-1}
K_{D-1}
$b_{N-3,i}$
$b_{N-2,i}$
$b_{N-1,i}$
3
$c_{0,i}$
$c_{1,i}$
$c_{2,i}$
$c_{N-3,i}$
$c_{N-2,i}$
$c_{N-1,i}$
7
s_k
8
$s(t)$
9
$\exp(j2\pi f_c t)$
x
$u(t)$

FIGURE 4A

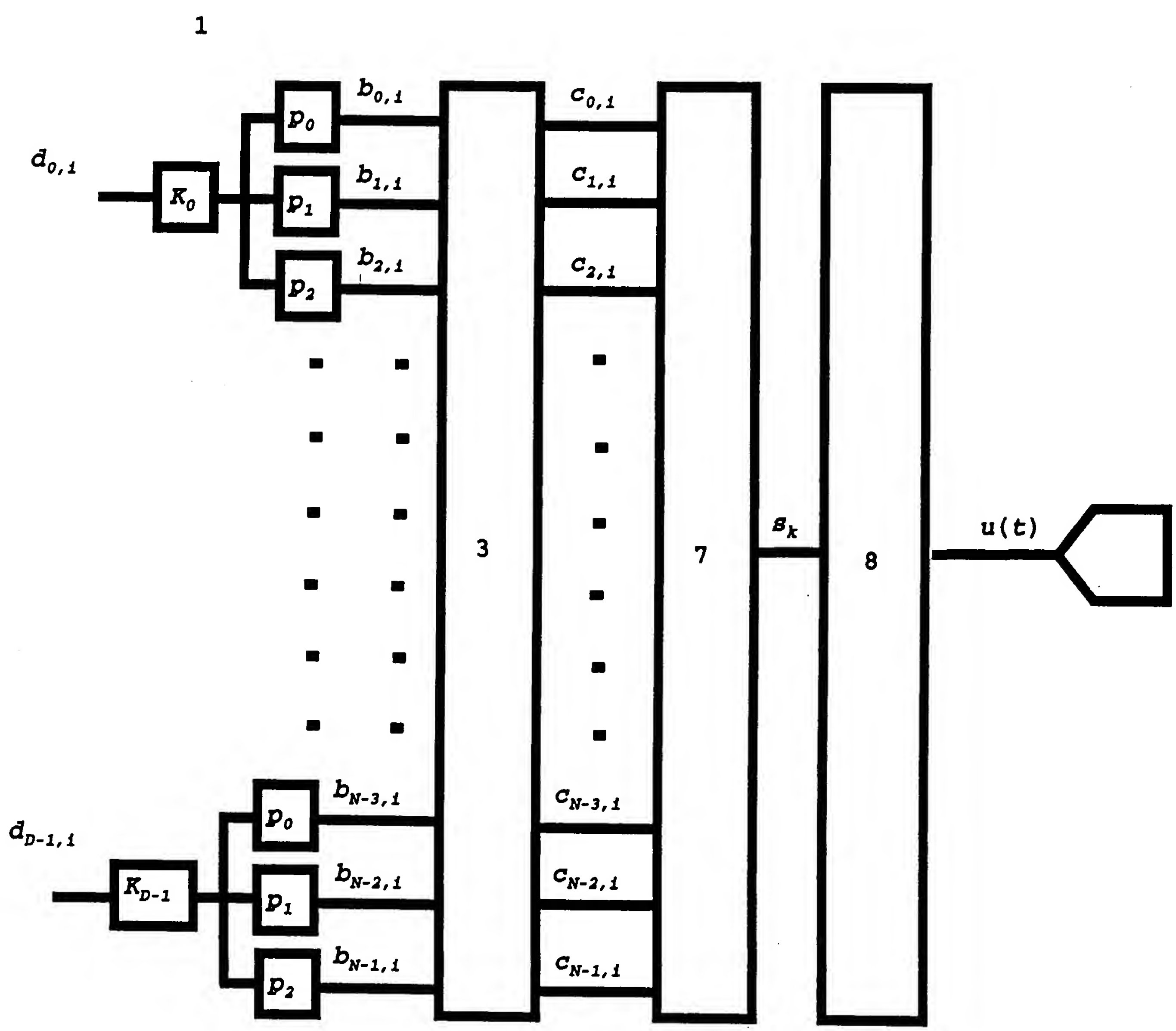
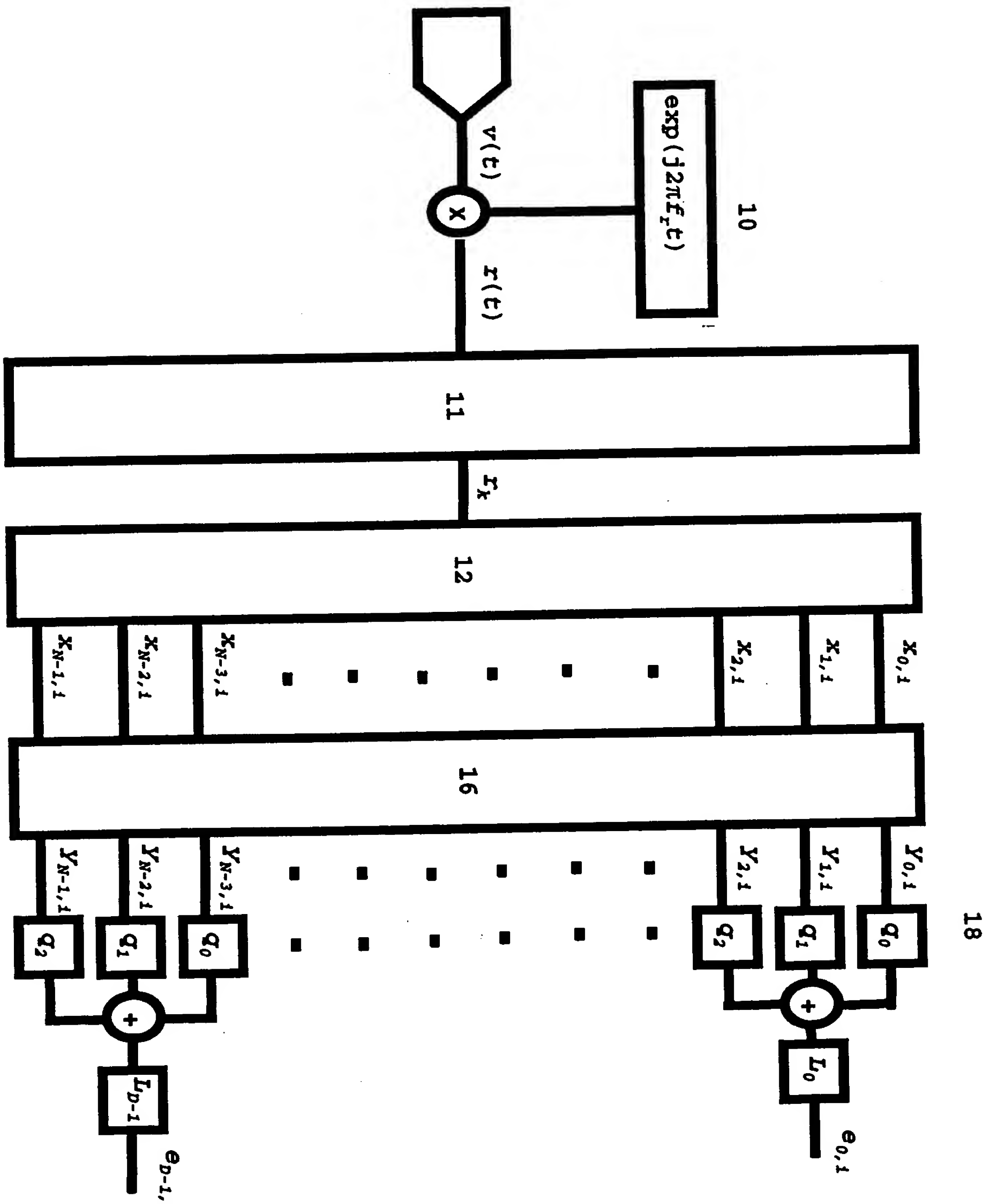
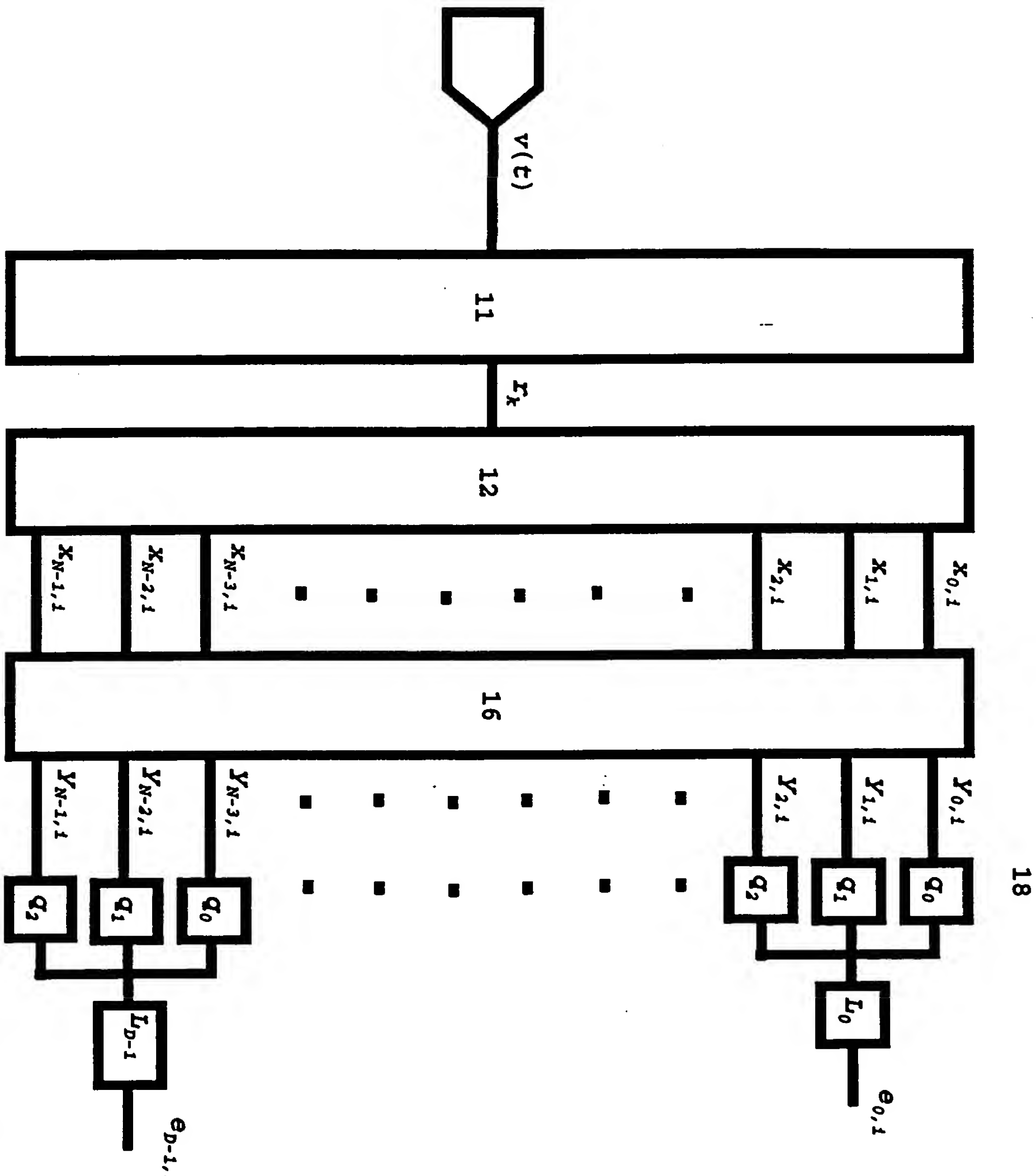

1
$d_{0,i}$
K_0
p_0
p_1
p_2
$b_{0,i}$
$b_{1,i}$
$b_{2,i}$
$d_{D-1,i}$
K_{D-1}
p_0
p_1
p_2
$b_{N-3,i}$
$b_{N-2,i}$
$b_{N-1,i}$
3
$c_{0,i}$
$c_{1,i}$
$c_{2,i}$
$c_{N-3,i}$
$c_{N-2,i}$
$c_{N-1,i}$
7
s_k
8
u(t)

FIGURE 4B



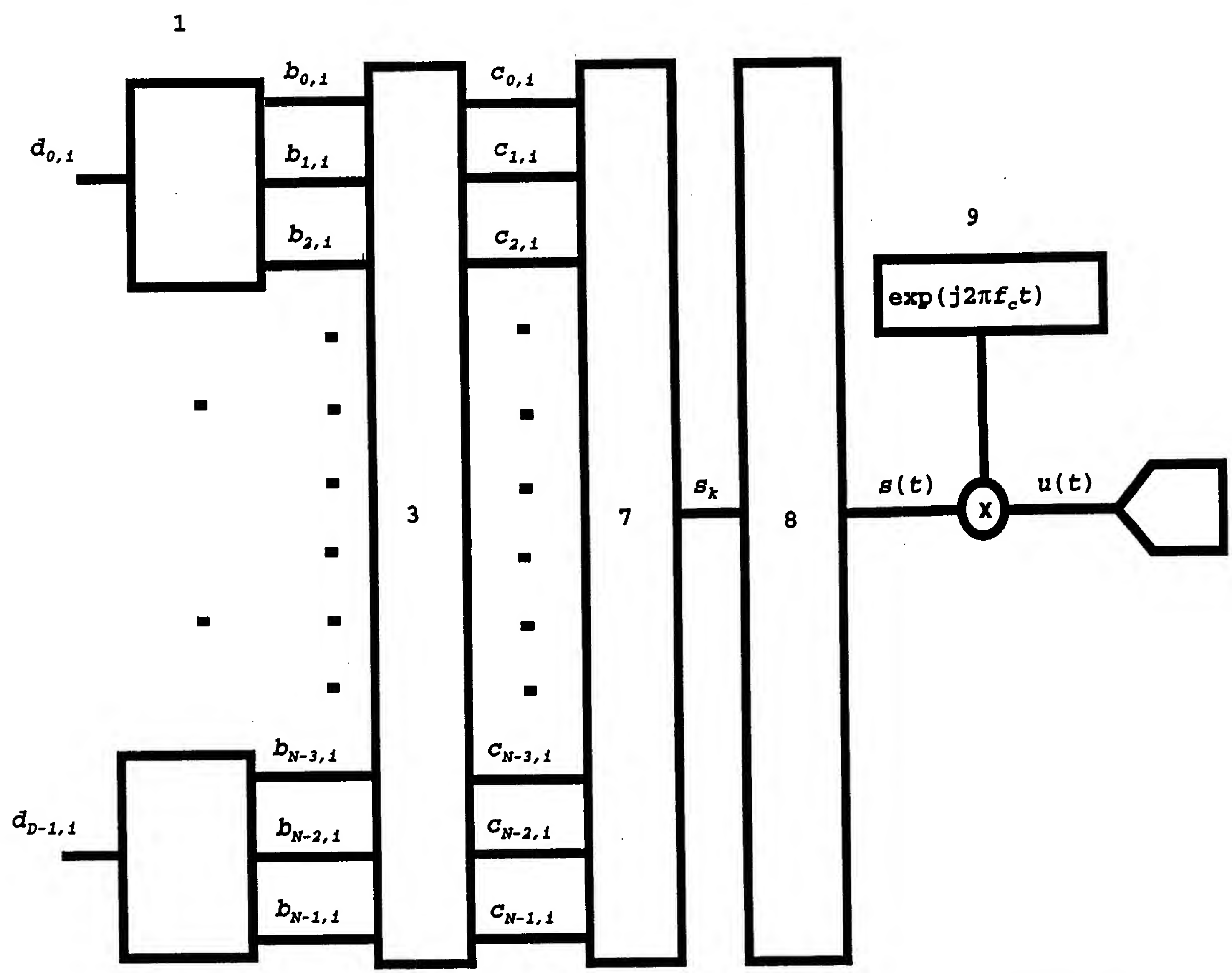
10
$\exp(j2\pi f_r t)$
$v(t)$
x
$r(t)$
11
r_k
12
$x_{N-1,1}$
$x_{N-2,1}$
$x_{N-3,1}$
$x_{2,1}$
$x_{1,1}$
$x_{0,1}$
16
$Y_{N-1,1}$
$Y_{N-2,1}$
$Y_{N-3,1}$
$Y_{2,1}$
$Y_{1,1}$
$Y_{0,1}$
18
q_2
q_1
q_0
+
L_0
L_{D-1}
$e_{0,1}$
$e_{D-1,1}$

FIGURE 5A



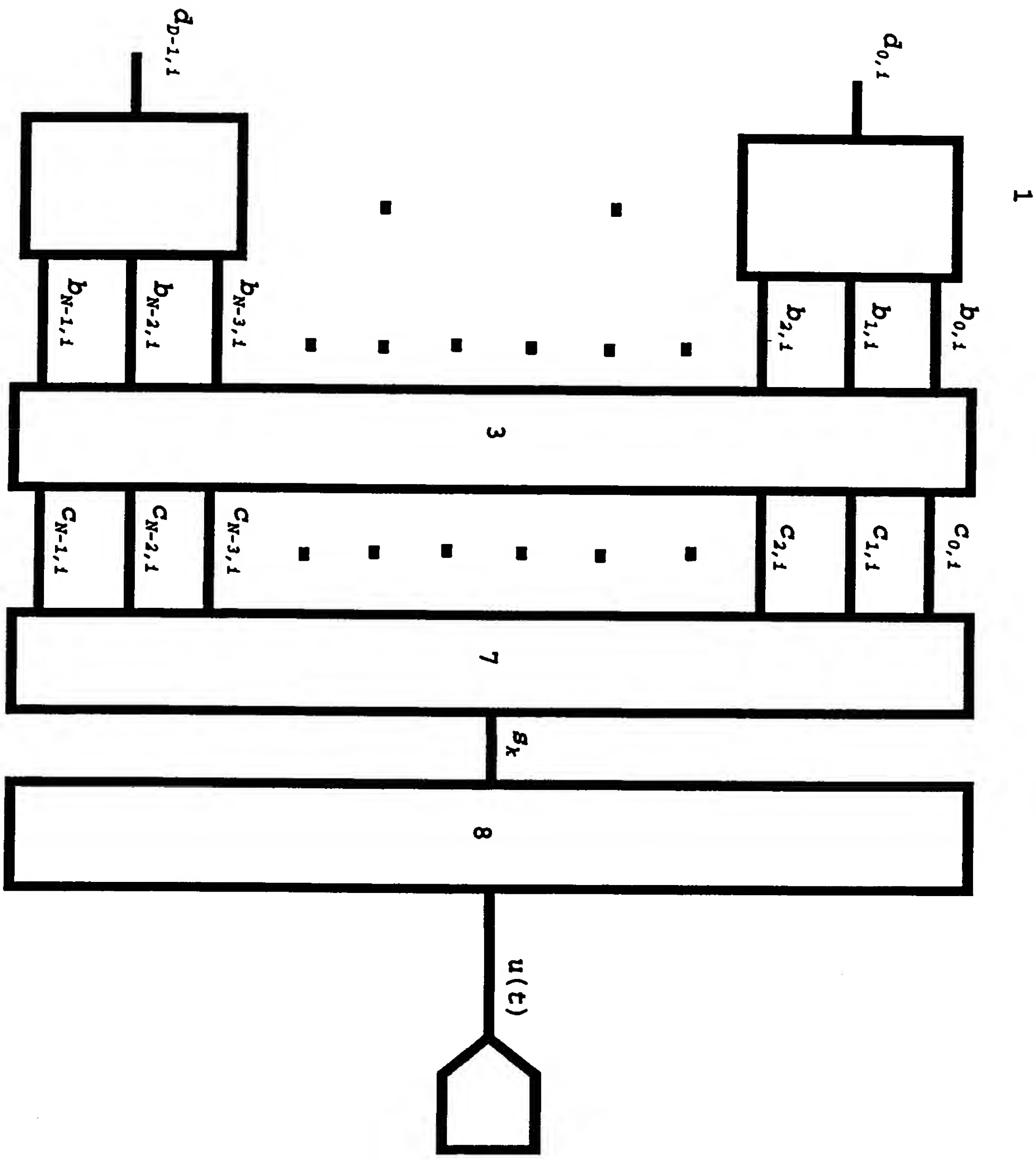
v(t)
11
r_k
12
$x_{N-1,1}$
$x_{N-2,1}$
$x_{N-3,1}$
$x_{2,1}$
$x_{1,1}$
$x_{0,1}$
16
$y_{N-1,1}$
$y_{N-2,1}$
$y_{N-3,1}$
$y_{2,1}$
$y_{1,1}$
$y_{0,1}$
18
q_2
q_1
q_0
q_2
q_1
q_0
L_0
L_{D-1}
$e_{0,1}$
$e_{D-1,1}$

FIGURE 5B



1
$d_{0,i}$
$b_{0,i}$
$b_{1,i}$
$b_{2,i}$
$d_{D-1,i}$
$b_{N-3,i}$
$b_{N-2,i}$
$b_{N-1,i}$
3
$c_{0,i}$
$c_{1,i}$
$c_{2,i}$
$c_{N-3,i}$
$c_{N-2,i}$
$c_{N-1,i}$
7
s_k
8
$s(t)$
9
$\exp(j2\pi f_c t)$
X
$u(t)$

FIGURE 6A



$d_{D-1,1}$
$d_{0,1}$
1
$b_{N-1,1}$
$b_{N-2,1}$
$b_{N-3,1}$
$b_{2,1}$
$b_{1,1}$
$b_{0,1}$
3
$c_{N-1,1}$
$c_{N-2,1}$
$c_{N-3,1}$
$c_{2,1}$
$c_{1,1}$
$c_{0,1}$
7
g_k
8
u(t)

FIGURE 6B

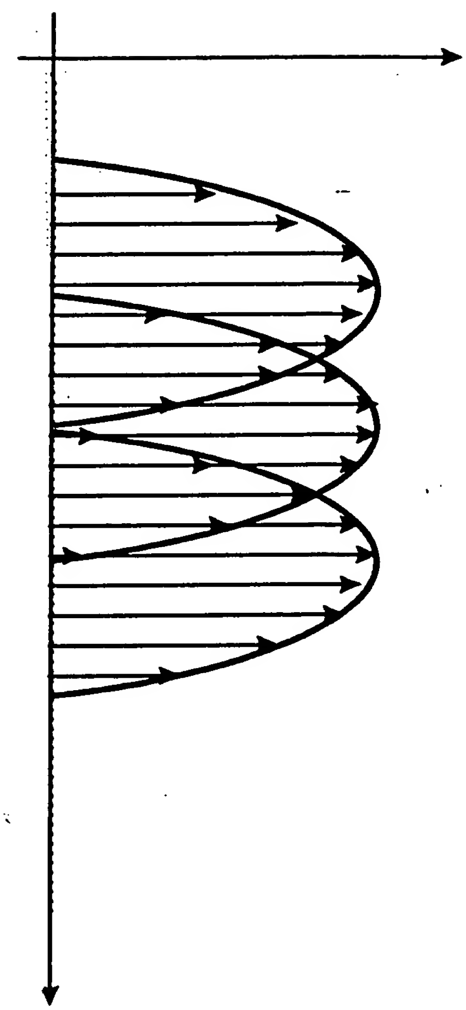
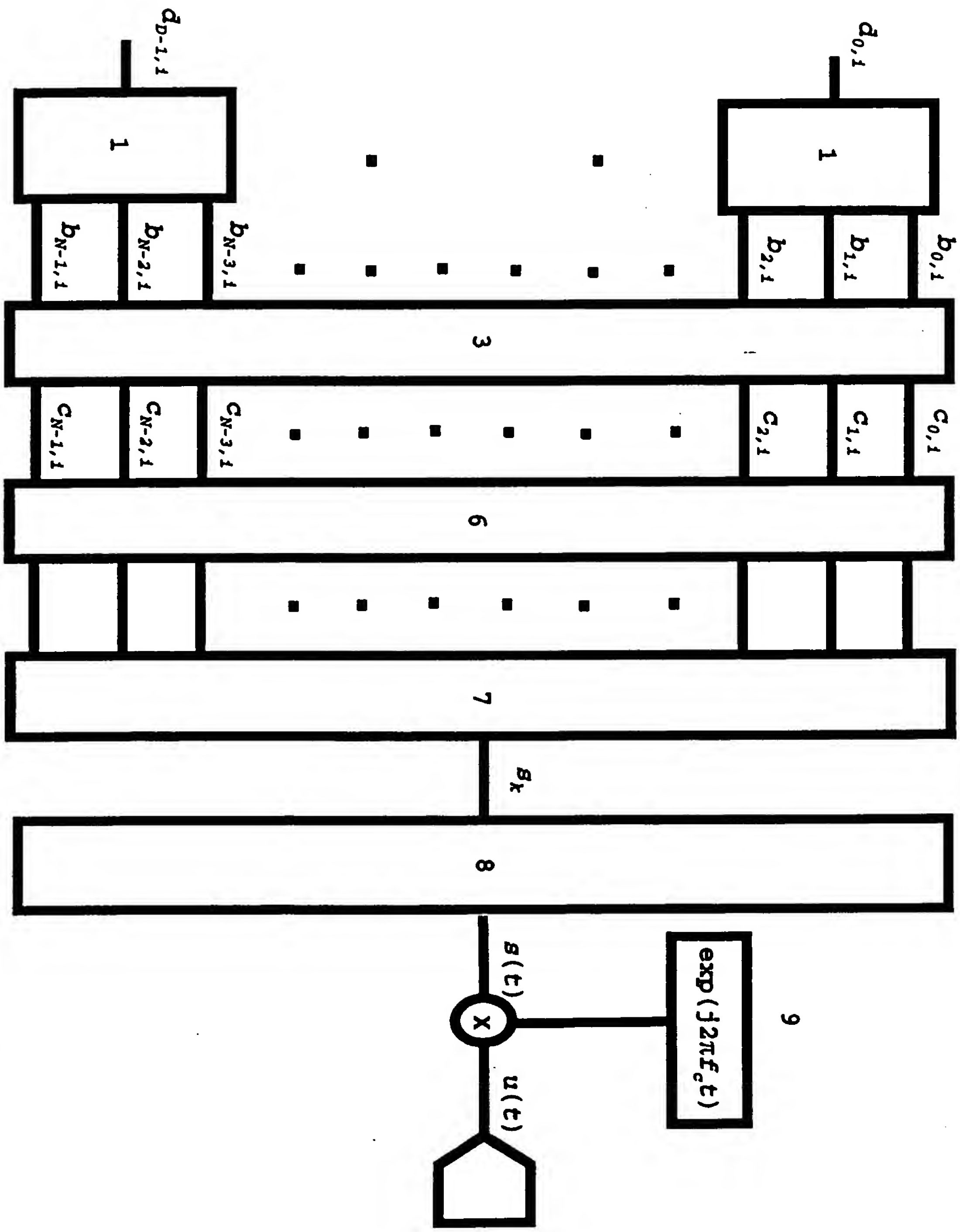


FIGURE 7



d_{D-1,1}
d_{0,1}
1
1
b_{N-1,1}
b_{N-2,1}
b_{N-3,1}
b_{2,1}
b_{1,1}
b_{0,1}
3
C_{N-1,1}
C_{N-2,1}
C_{N-3,1}
C_{2,1}
C_{1,1}
C_{0,1}
6
7
s_k
8
s(t)
X
u(t)
exp(j2πf_c t)
9

FIGURE 8A

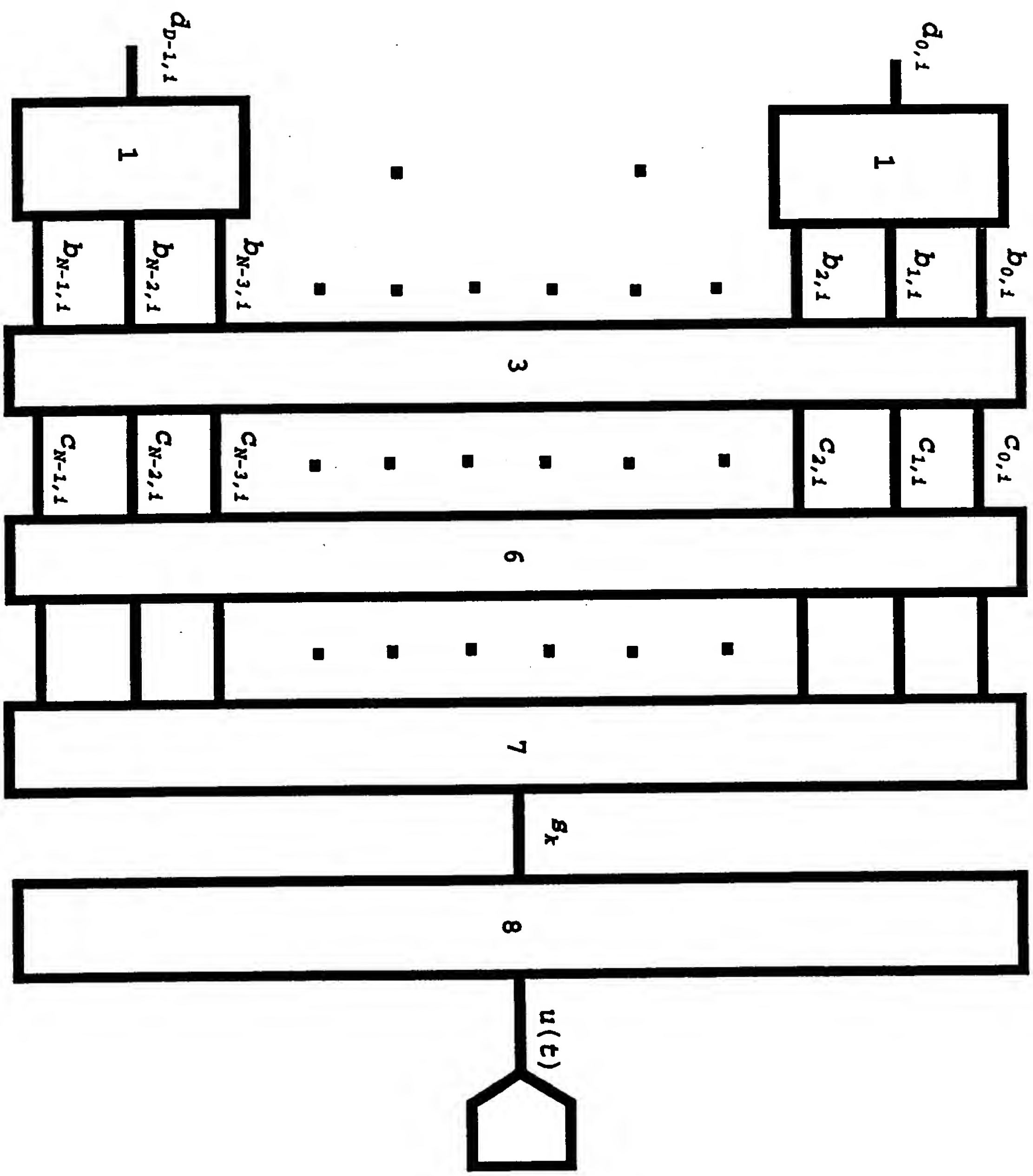
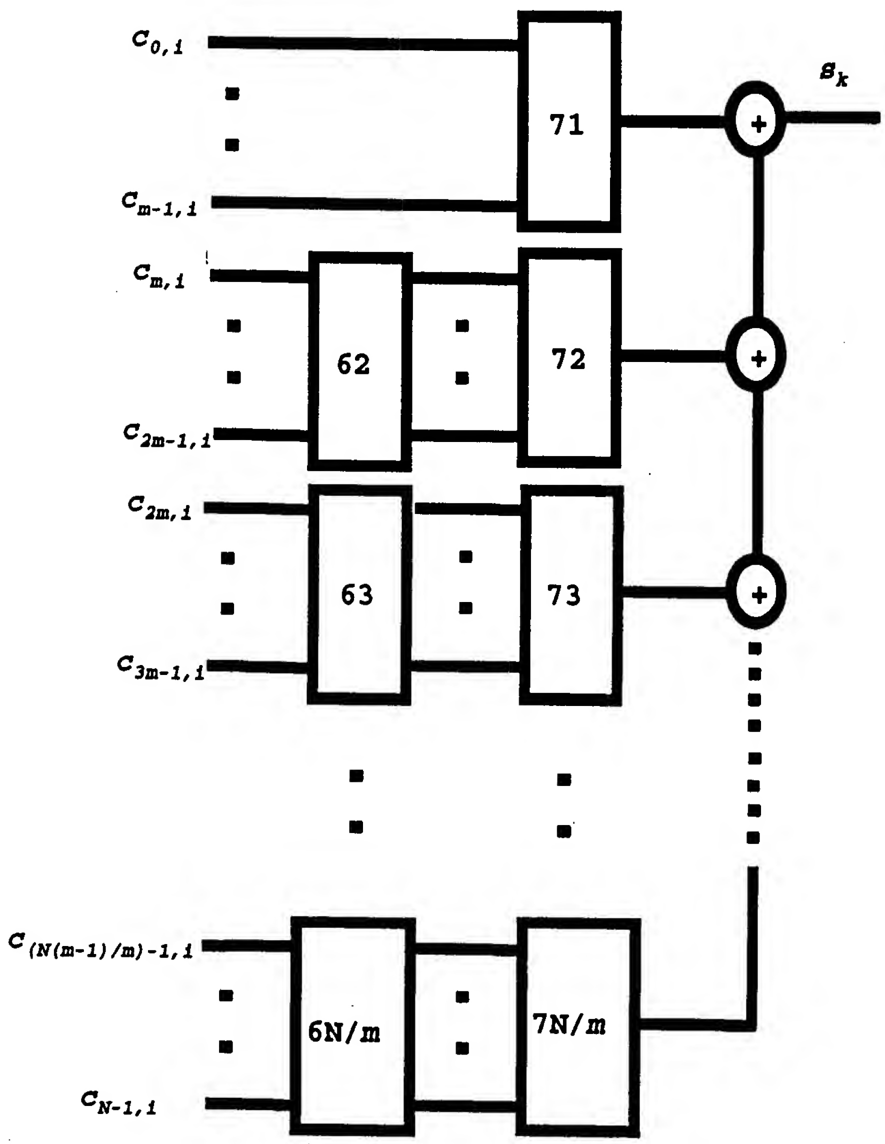

d_{D-1,1}
d_{0,1}
1
1
b_{N-1,1}
b_{N-2,1}
b_{N-3,1}
b_{2,1}
b_{1,1}
b_{0,1}
3
c_{N-1,1}
c_{N-2,1}
c_{N-3,1}
c_{2,1}
c_{1,1}
c_{0,1}
6
7
8
u(t)

FIGURE 8B



$c_{0,i}$
$c_{m-1,i}$
$c_{m,i}$
$c_{2m-1,i}$
$c_{2m,i}$
$c_{3m-1,i}$
$c_{(N(m-1)/m)-1,i}$
$c_{N-1,i}$
71
62
72
63
73
6N/m
7N/m
+
+
+
s_k

FIGURE 8C

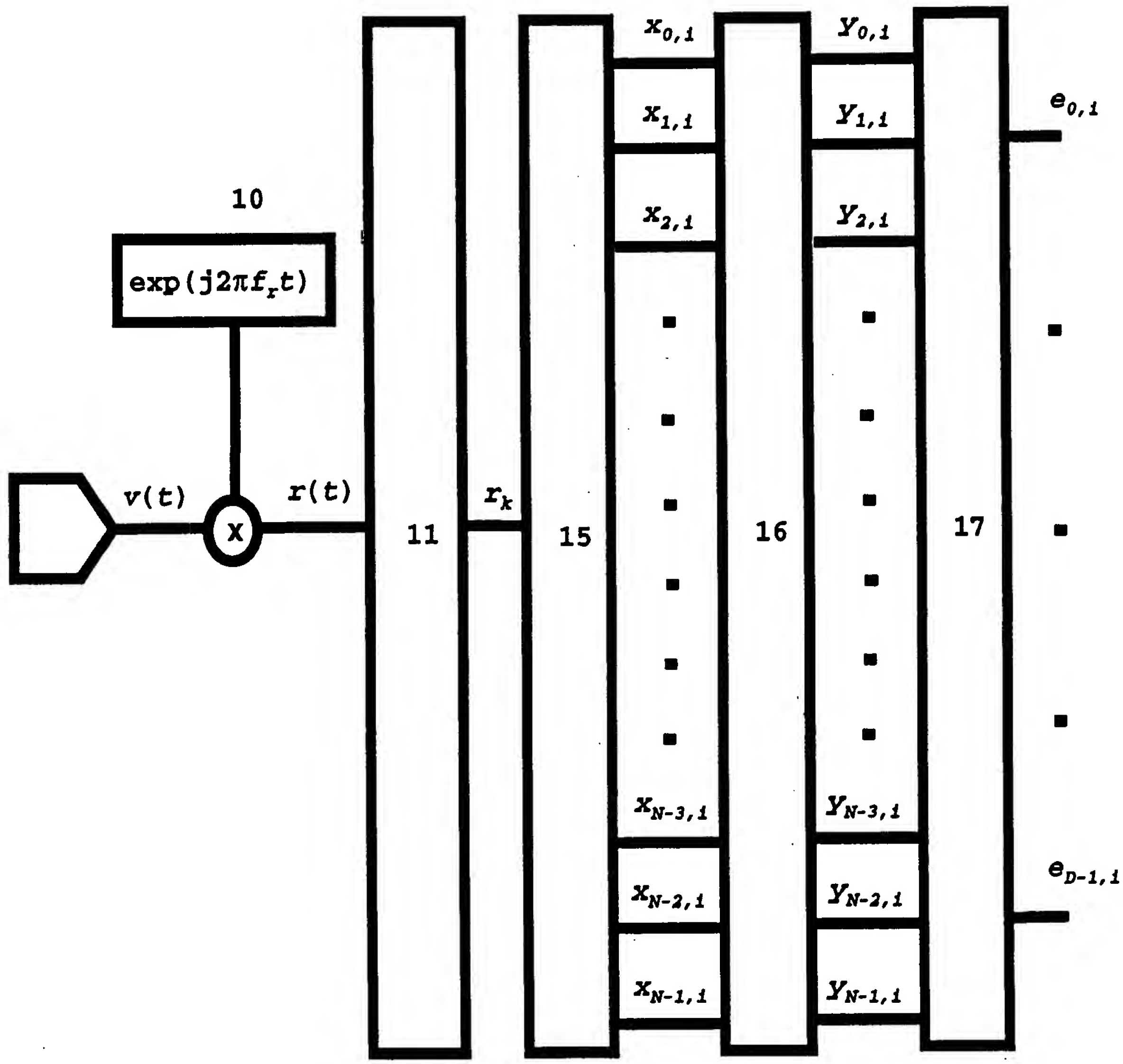

10
exp(j2πf_r t)
v(t)
x
r(t)
11
r_k
15
x_{0,i}
x_{1,i}
x_{2,i}
x_{N-3,i}
x_{N-2,i}
x_{N-1,i}
16
y_{0,i}
y_{1,i}
y_{2,i}
y_{N-3,i}
y_{N-2,i}
y_{N-1,i}
17
e_{0,i}
e_{D-1,i}

FIGURE 9A

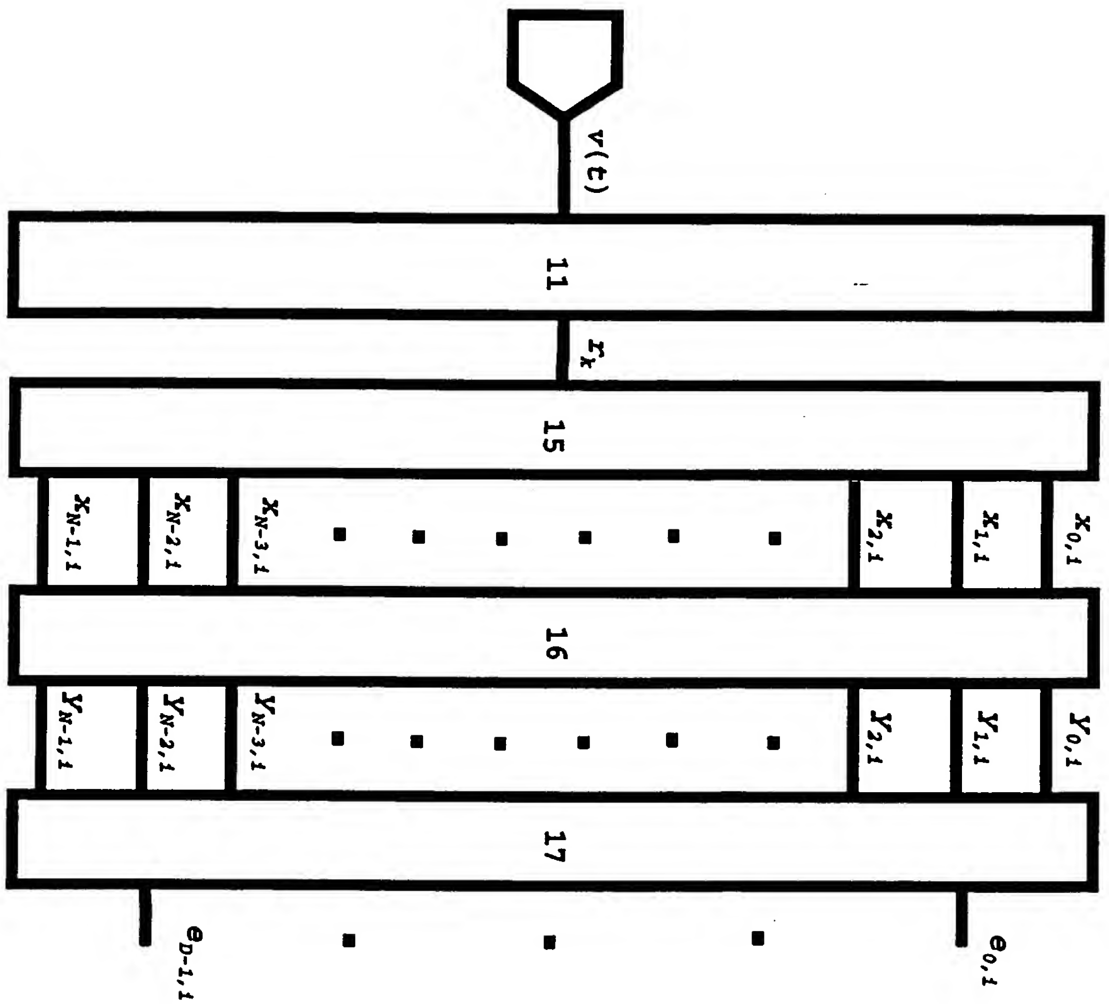

v(t)
11
r_k
15
$x_{N-1,1}$
$x_{N-2,1}$
$x_{N-3,1}$
$x_{2,1}$
$x_{1,1}$
$x_{0,1}$
16
$Y_{N-1,1}$
$Y_{N-2,1}$
$Y_{N-3,1}$
$Y_{2,1}$
$Y_{1,1}$
$Y_{0,1}$
17
$e_{D-1,1}$
$e_{0,1}$

FIGURE 9B

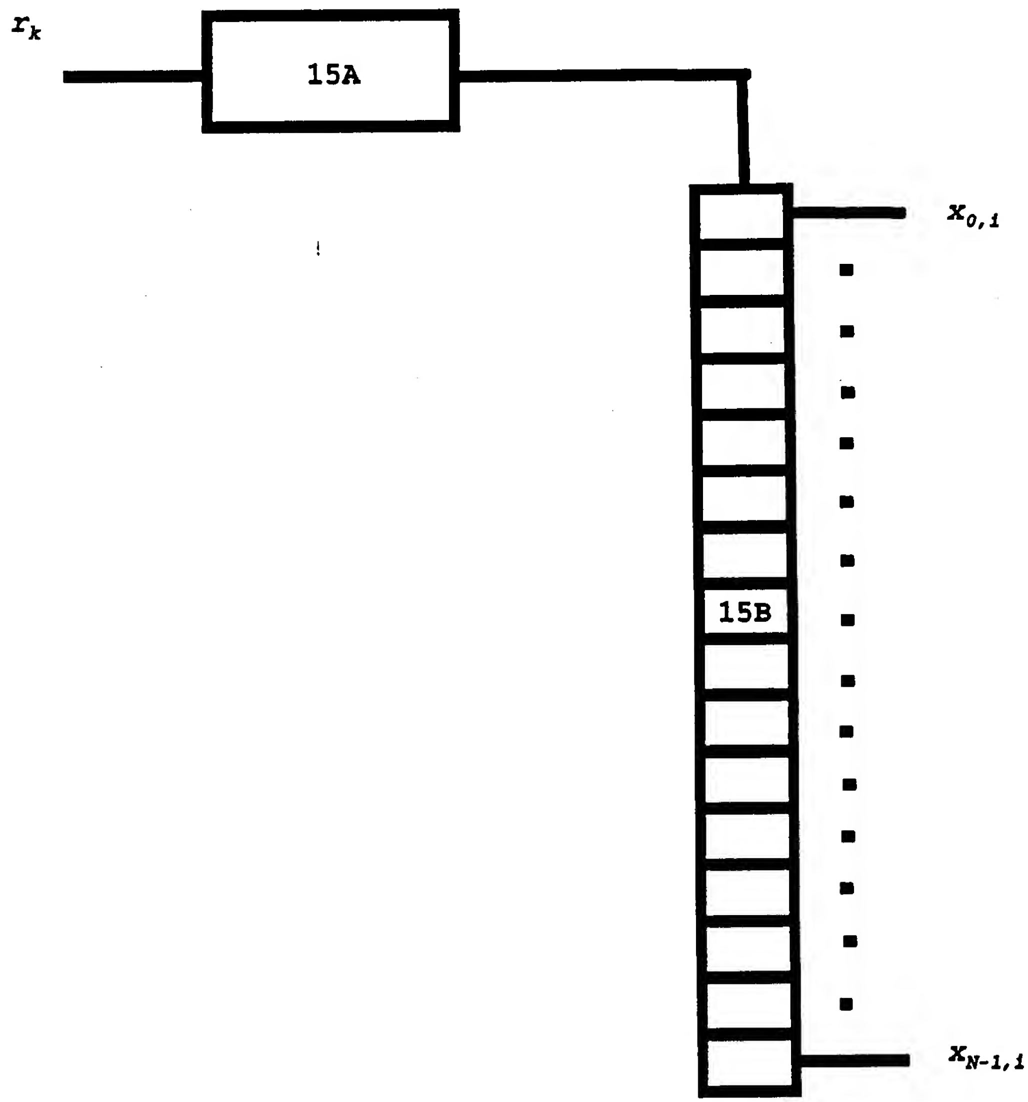
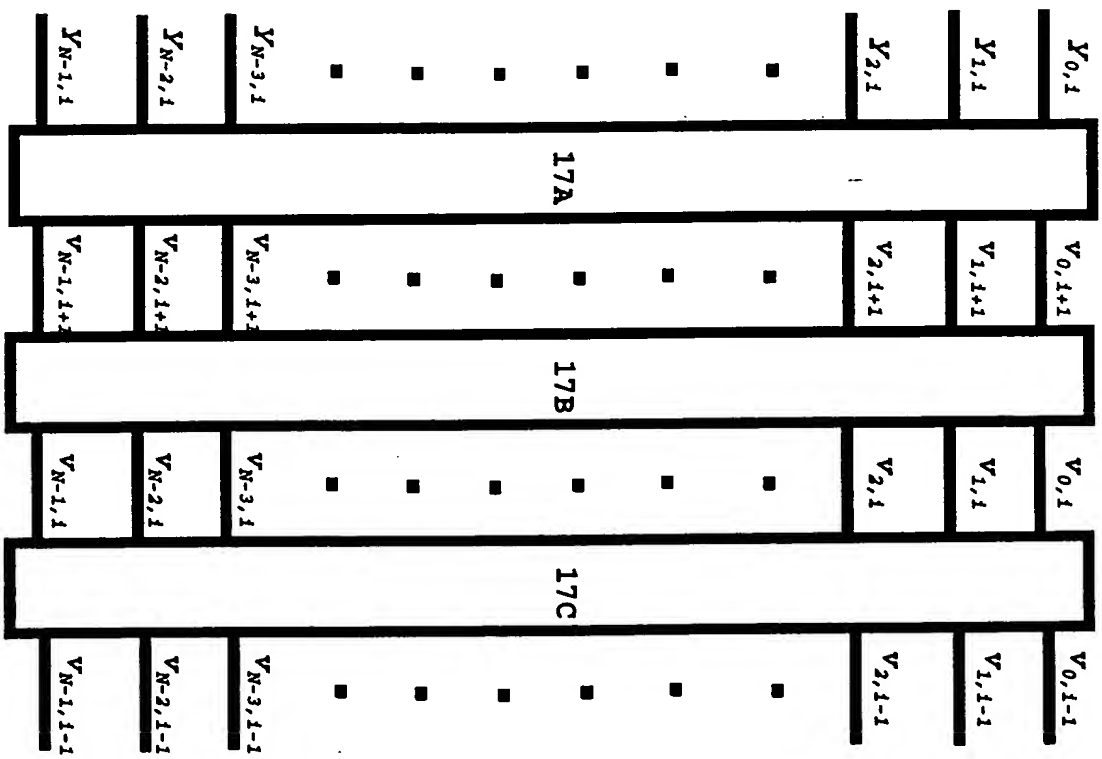


FIGURE 9C



$Y_{N-1,i}$
$Y_{N-2,i}$
$Y_{N-3,i}$
$Y_{2,i}$
$Y_{1,i}$
$Y_{0,i}$
17A
$V_{N-1,i+1}$
$V_{N-2,i+1}$
$V_{N-3,i+1}$
$V_{2,i+1}$
$V_{1,i+1}$
$V_{0,i+1}$
17B
$V_{N-1,i}$
$V_{N-2,i}$
$V_{N-3,i}$
$V_{2,i}$
$V_{1,i}$
$V_{0,i}$
17C
$V_{N-1,i-1}$
$V_{N-2,i-1}$
$V_{N-3,i-1}$
$V_{2,i-1}$
$V_{1,i-1}$
$V_{0,i-1}$

FIGURE 10

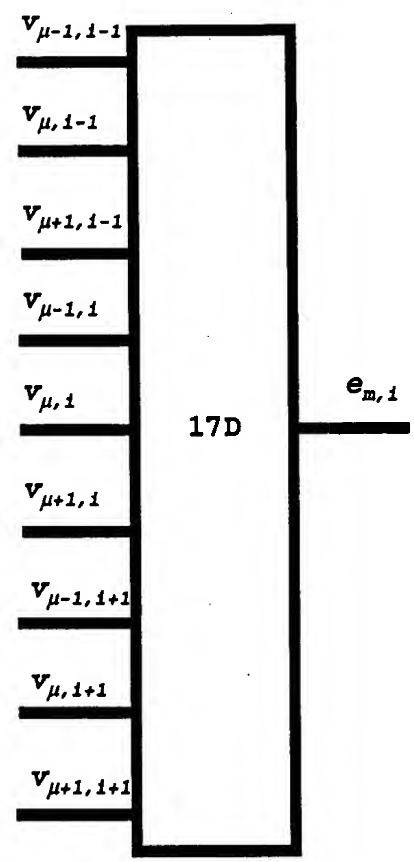
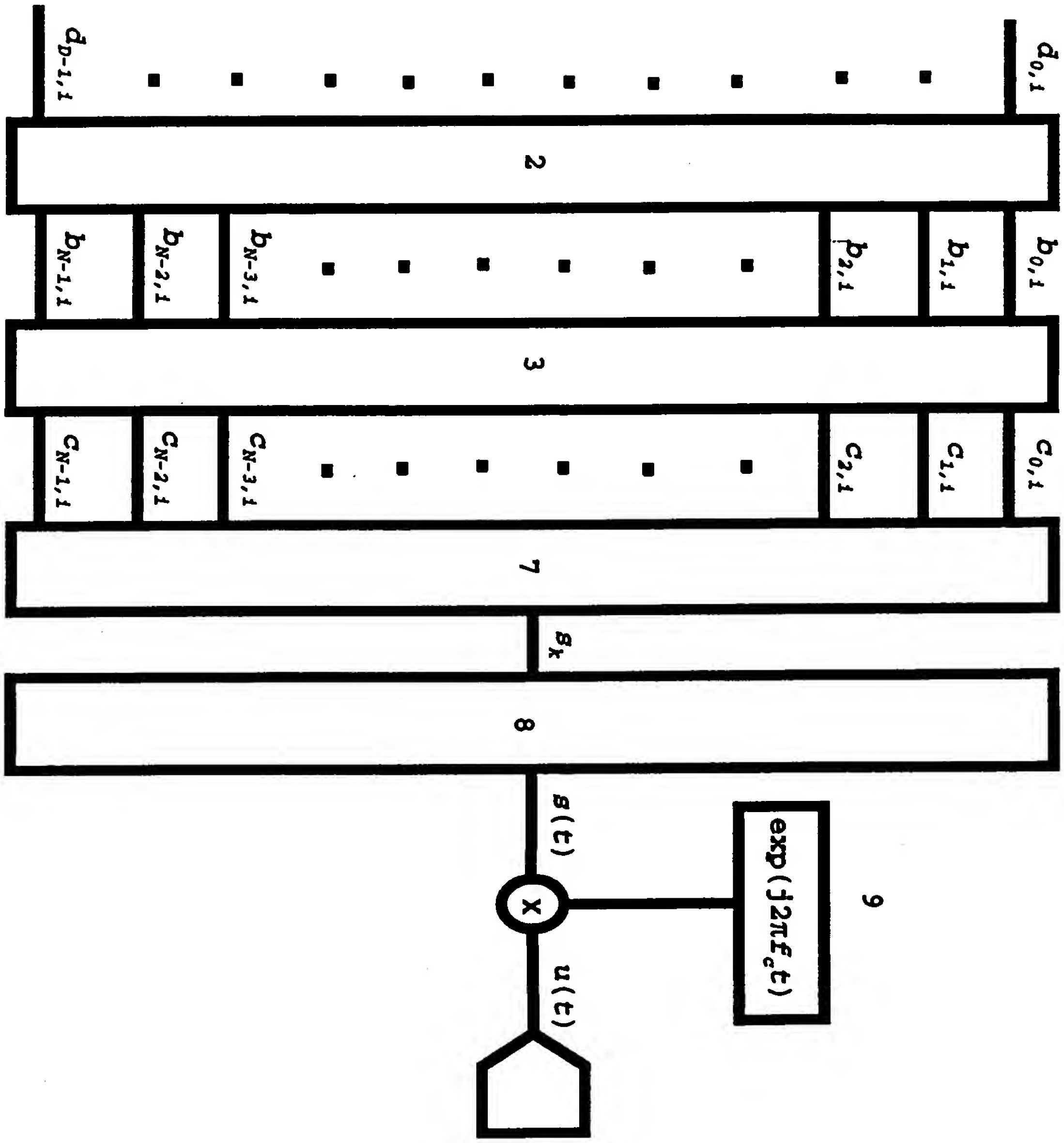
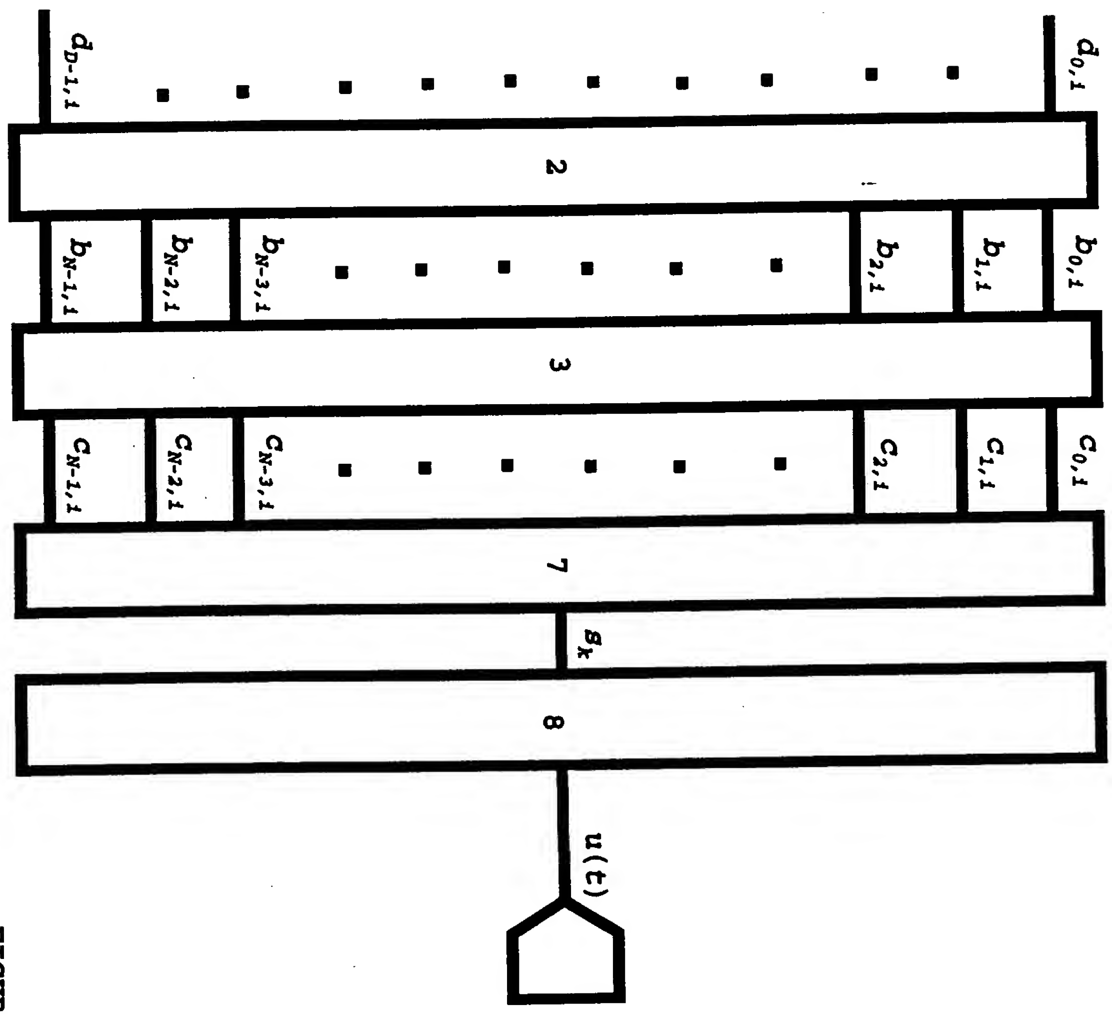

$v_{\mu-1,i-1}$
$v_{\mu,i-1}$
$v_{\mu+1,i-1}$
$v_{\mu-1,i}$
$v_{\mu,i}$
$v_{\mu+1,i}$
$v_{\mu-1,i+1}$
$v_{\mu,i+1}$
$v_{\mu+1,i+1}$
17D
$e_{m,i}$

FIGURE 11



$d_{0,1}$
$d_{D-1,1}$
2
$b_{0,1}$
$b_{1,1}$
$b_{2,1}$
$b_{N-3,1}$
$b_{N-2,1}$
$b_{N-1,1}$
3
$c_{0,1}$
$c_{1,1}$
$c_{2,1}$
$c_{N-3,1}$
$c_{N-2,1}$
$c_{N-1,1}$
7
s_k
8
$s(t)$
X
9
$\exp(j2\pi f_c t)$
$u(t)$

FIGURE 12A



$d_{0,1}$
$d_{D-1,1}$
2
$b_{0,1}$
$b_{1,1}$
$b_{2,1}$
$b_{N-3,1}$
$b_{N-2,1}$
$b_{N-1,1}$
3
$C_{0,1}$
$C_{1,1}$
$C_{2,1}$
$C_{N-3,1}$
$C_{N-2,1}$
$C_{N-1,1}$
7
s_k
8
u(t)

FIGURE 12B

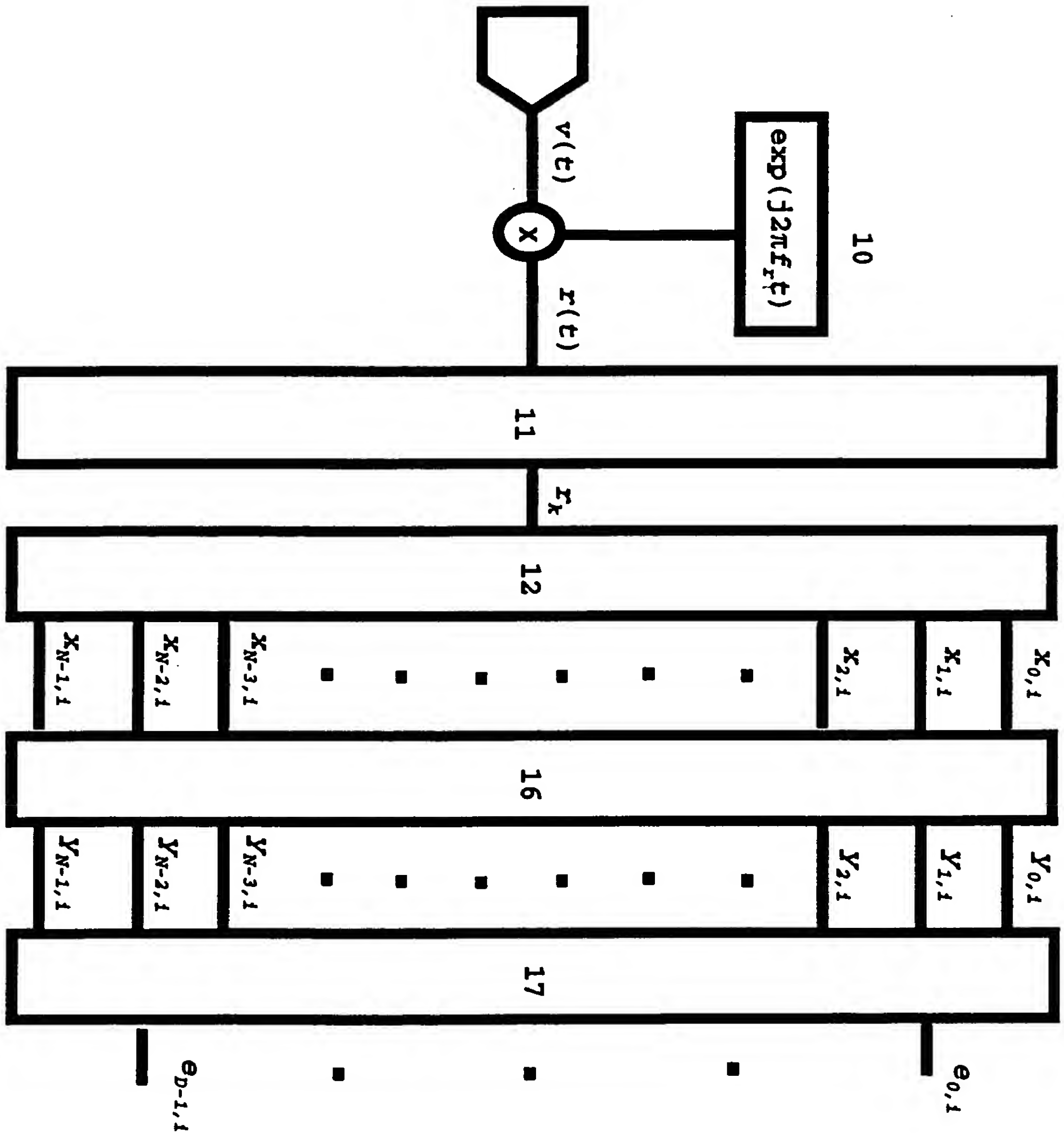

10
exp(j2πf_rt)
v(t)
x
r(t)
11
r_k
12
X_{N-1,l}
X_{N-2,l}
X_{N-3,l}
X_{2,l}
X_{1,l}
X_{0,l}
16
Y_{N-1,l}
Y_{N-2,l}
Y_{N-3,l}
Y_{2,l}
Y_{1,l}
Y_{0,l}
17
e_{D-1,l}
e_{0,l}

FIGURE 12C

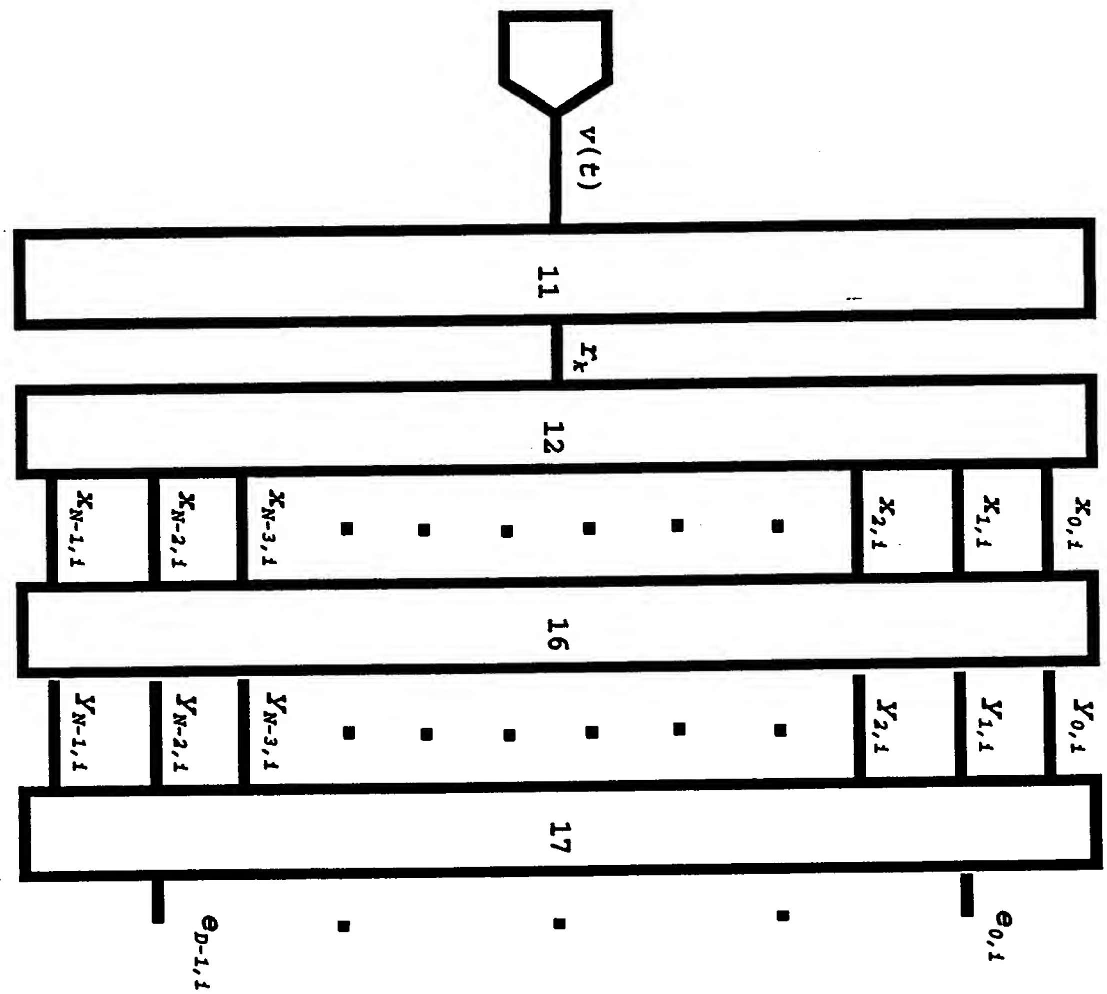

v(t)
11
r_k
12
$x_{N-1,i}$
$x_{N-2,i}$
$x_{N-3,i}$
$x_{2,i}$
$x_{1,i}$
$x_{0,i}$
16
$y_{N-1,i}$
$y_{N-2,i}$
$y_{N-3,i}$
$y_{2,i}$
$y_{1,i}$
$y_{0,i}$
17
$e_{D-1,i}$
$e_{0,i}$

FIGURE 12D

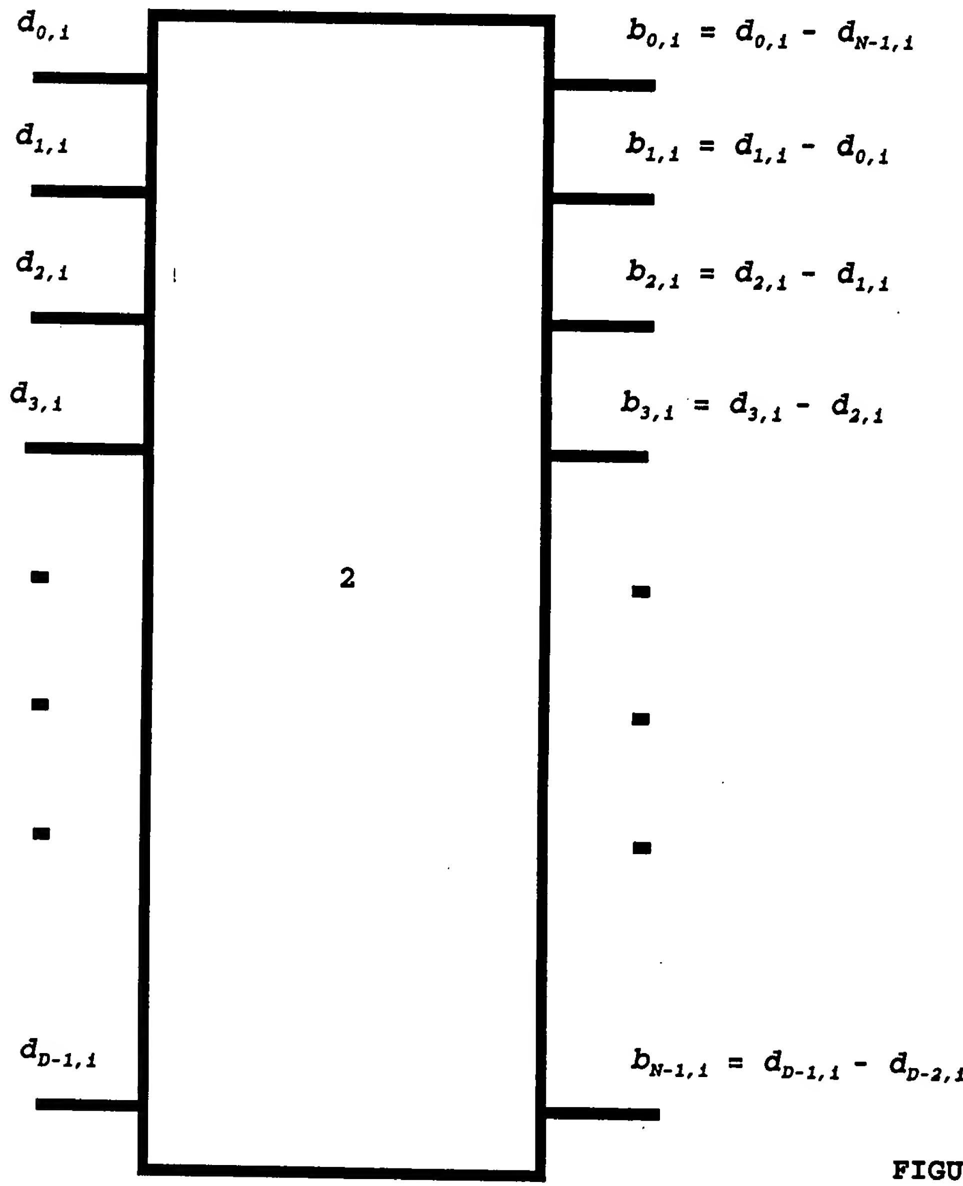

$d_{0,i}$
$d_{1,i}$
$d_{2,i}$
$d_{3,i}$
$d_{D-1,i}$
2
$b_{0,i} = d_{0,i} - d_{N-1,i}$
$b_{1,i} = d_{1,i} - d_{0,i}$
$b_{2,i} = d_{2,i} - d_{1,i}$
$b_{3,i} = d_{3,i} - d_{2,i}$
$b_{N-1,i} = d_{D-1,i} - d_{D-2,i}$

FIGURE 13A

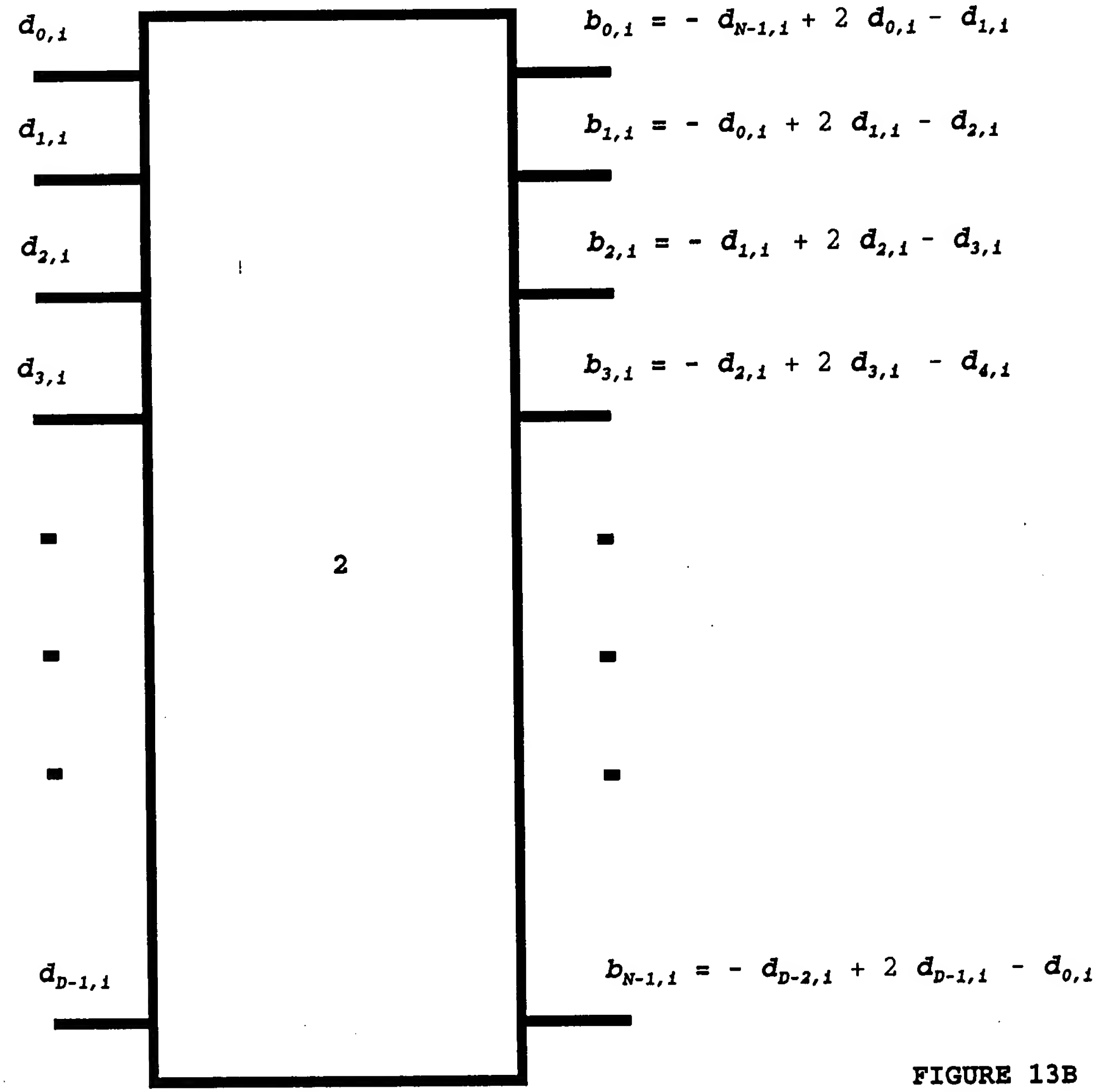

$d_{0,i}$
$d_{1,i}$
$d_{2,i}$
$d_{3,i}$
$d_{D-1,i}$
2
$b_{0,i} = - d_{N-1,i} + 2\ d_{0,i} - d_{1,i}$
$b_{1,i} = - d_{0,i} + 2\ d_{1,i} - d_{2,i}$
$b_{2,i} = - d_{1,i} + 2\ d_{2,i} - d_{3,i}$
$b_{3,i} = - d_{2,i} + 2\ d_{3,i} - d_{4,i}$
$b_{N-1,i} = - d_{D-2,i} + 2\ d_{D-1,i} - d_{0,i}$

FIGURE 13B

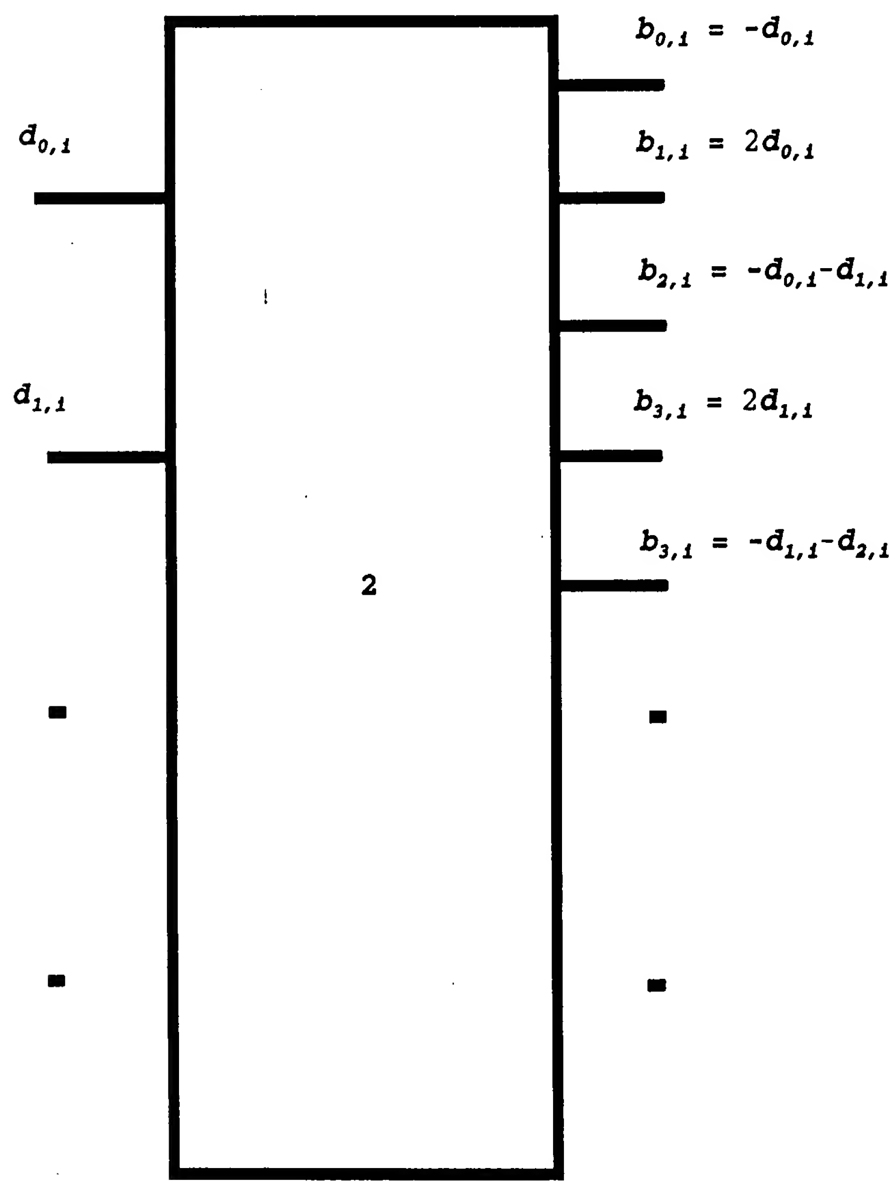


FIGURE 13C

<date/time>

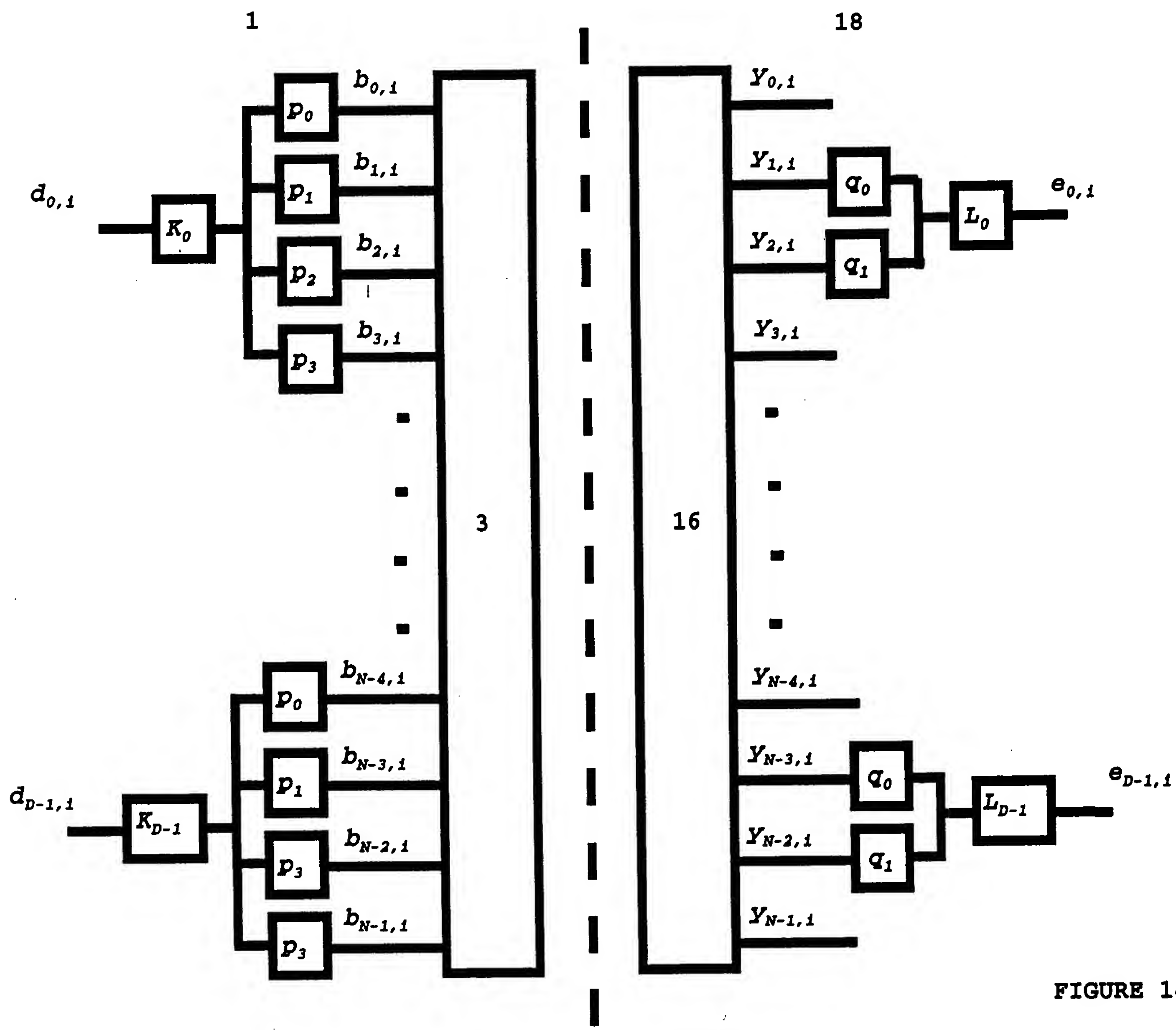
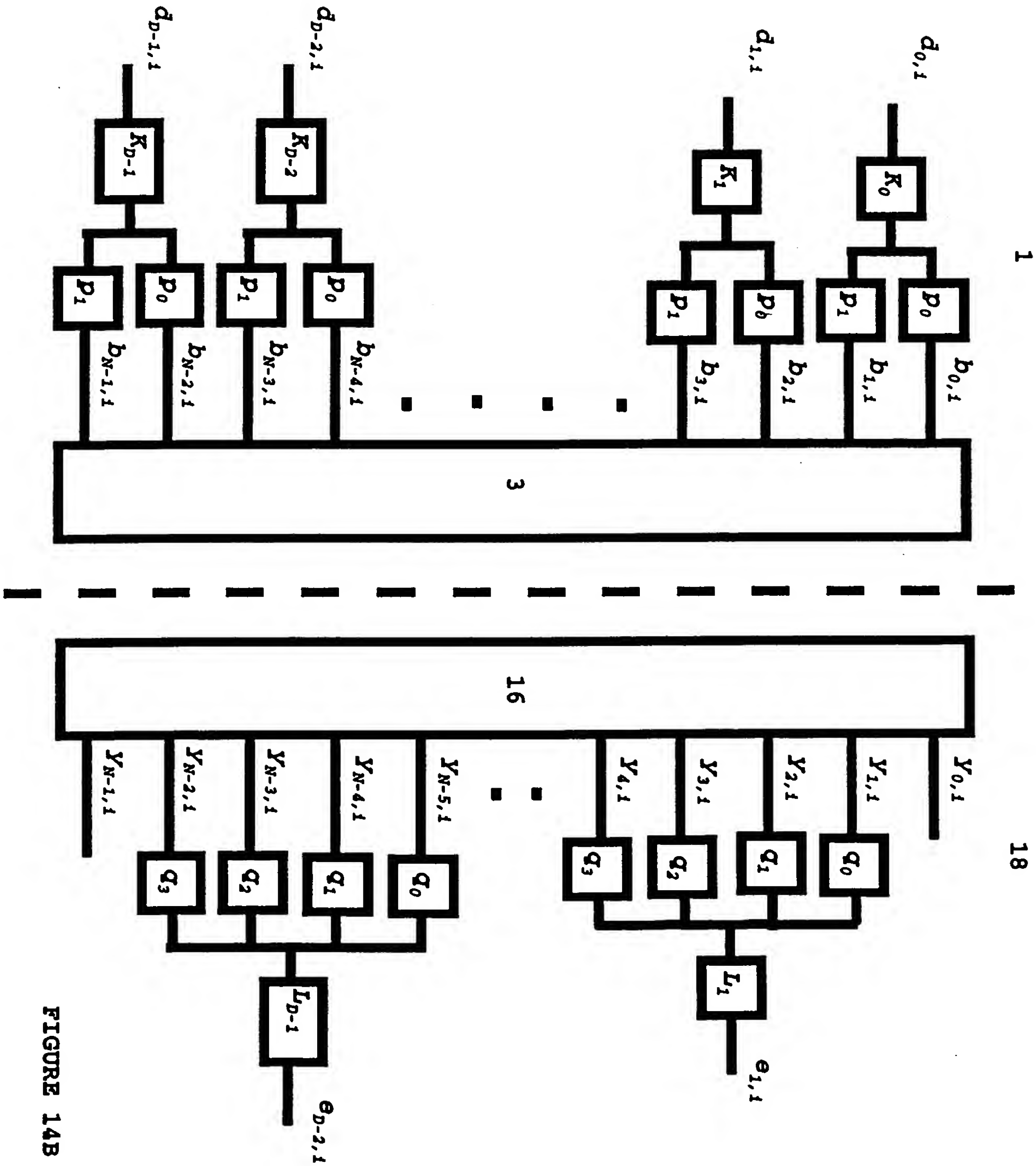

1
18
$d_{0,i}$
K_0
p_0
p_1
p_2
p_3
$b_{0,i}$
$b_{1,i}$
$b_{2,i}$
$b_{3,i}$
$d_{D-1,i}$
K_{D-1}
p_0
p_1
p_3
p_3
$b_{N-4,i}$
$b_{N-3,i}$
$b_{N-2,i}$
$b_{N-1,i}$
3
16
$Y_{0,i}$
$Y_{1,i}$
$Y_{2,i}$
$Y_{3,i}$
q_0
q_1
L_0
$e_{0,i}$
$Y_{N-4,i}$
$Y_{N-3,i}$
$Y_{N-2,i}$
$Y_{N-1,i}$
q_0
q_1
L_{D-1}
$e_{D-1,i}$

FIGURE 14A



1
3
16
18
$d_{0,1}$
$d_{1,1}$
$d_{D-2,1}$
$d_{D-1,1}$
K_0
K_1
K_{D-2}
K_{D-1}
P_0
P_1
$b_{0,1}$
$b_{1,1}$
$b_{2,1}$
$b_{3,1}$
$b_{N-4,1}$
$b_{N-3,1}$
$b_{N-2,1}$
$b_{N-1,1}$
$Y_{0,1}$
$Y_{1,1}$
$Y_{2,1}$
$Y_{3,1}$
$Y_{4,1}$
$Y_{N-5,1}$
$Y_{N-4,1}$
$Y_{N-3,1}$
$Y_{N-2,1}$
$Y_{N-1,1}$
q_0
q_1
q_2
q_3
L_1
L_{D-1}
$e_{1,1}$
$e_{D-2,1}$

FIGURE 14B

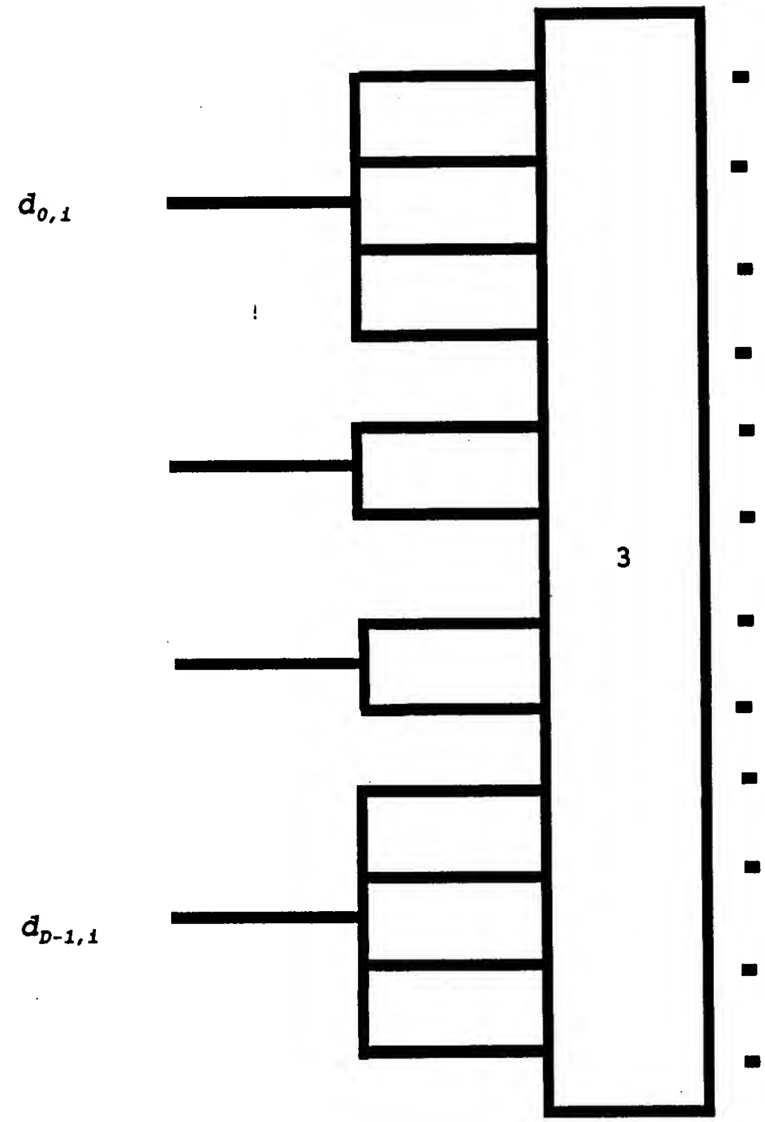


FIGURE 15

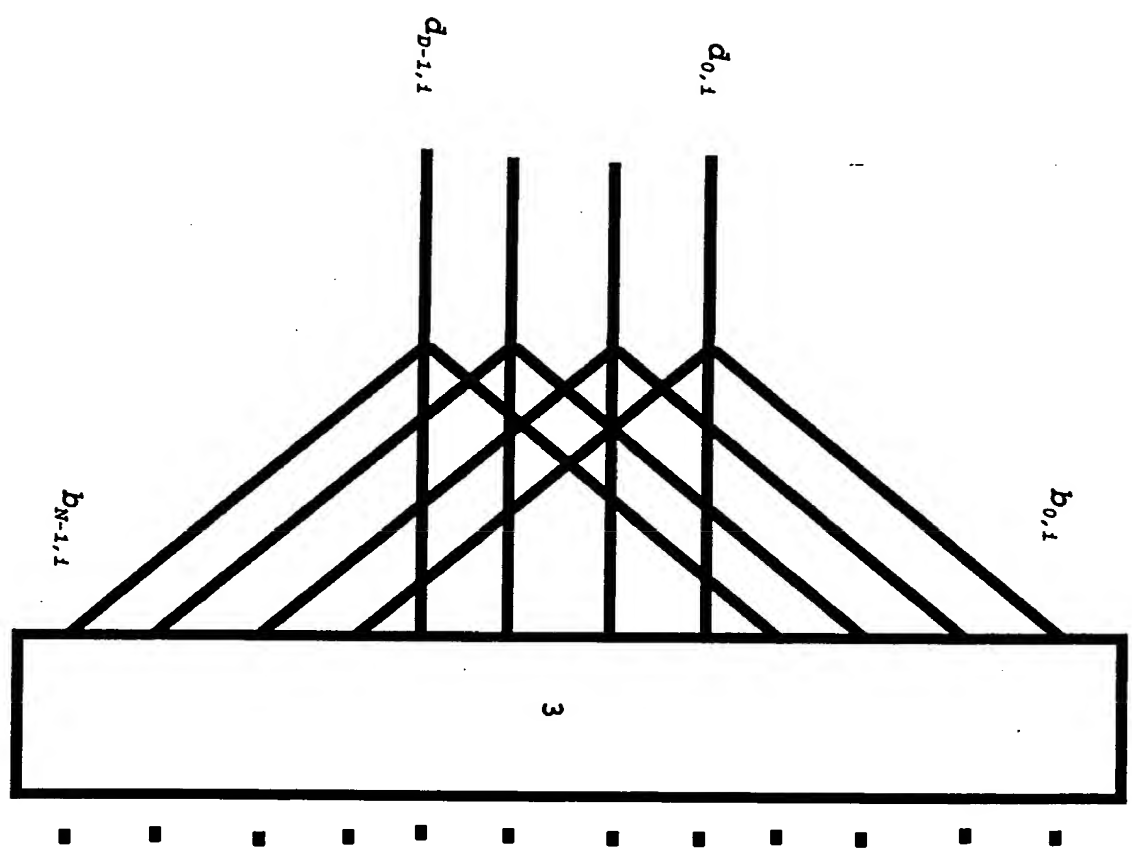
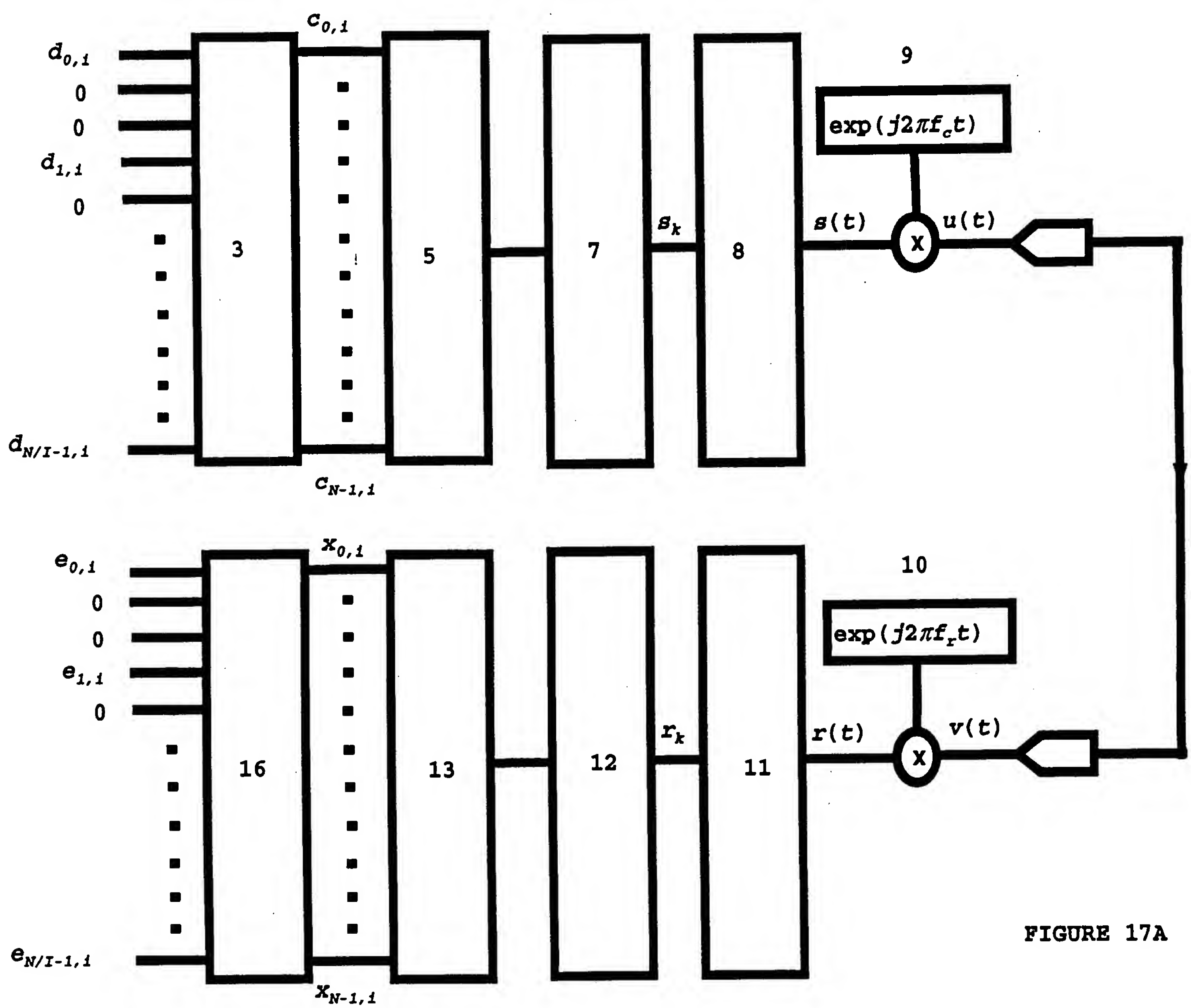
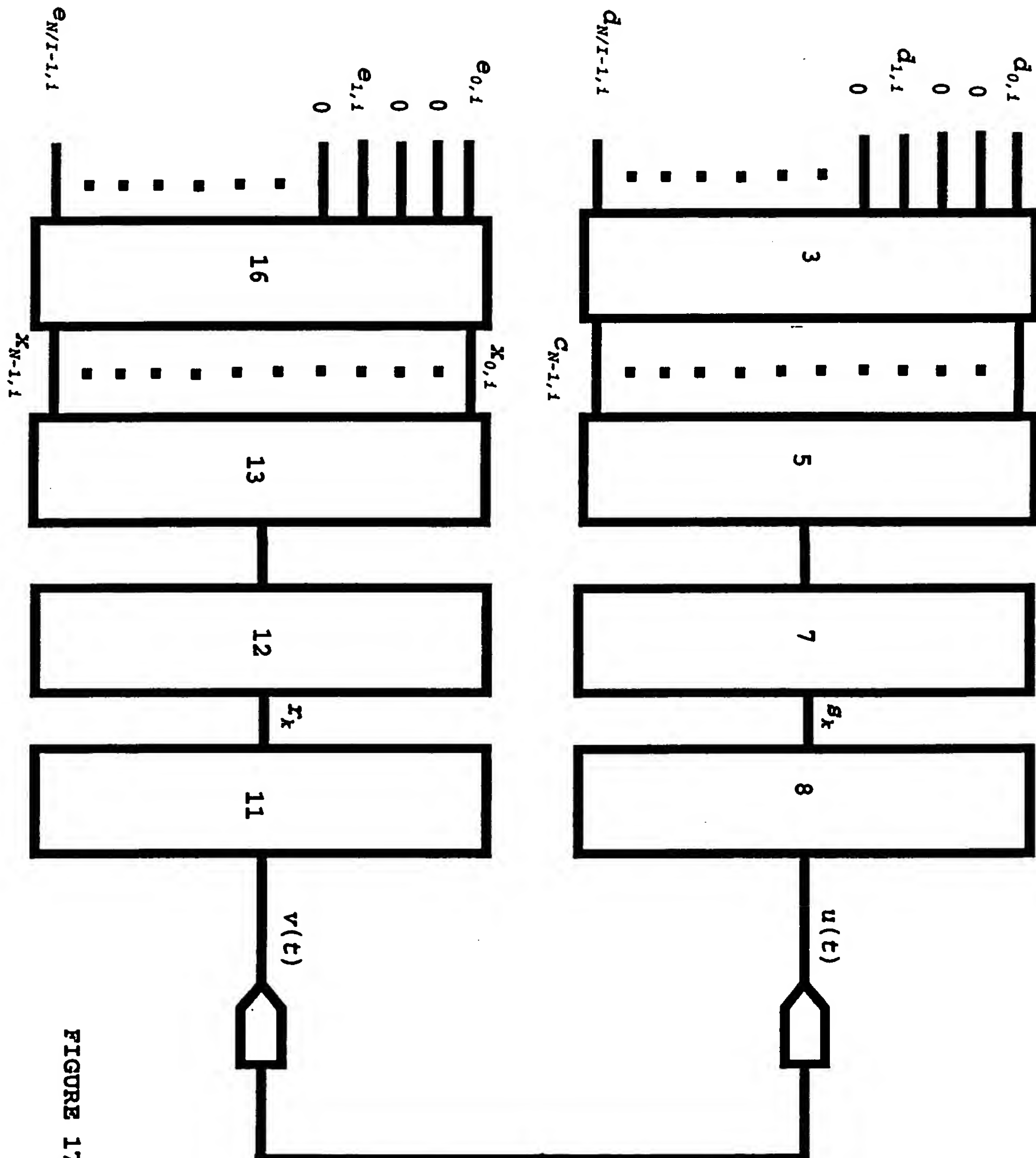


FIGURE 16



$d_{0,i}$
0
0
$d_{1,i}$
0
$d_{N/I-1,i}$
3
$c_{0,i}$
$c_{N-1,i}$
5
7
s_k
8
9
$\exp(j2\pi f_c t)$
$s(t)$
X
$u(t)$
$e_{0,i}$
0
0
$e_{1,i}$
0
$e_{N/I-1,i}$
16
$x_{0,i}$
$x_{N-1,i}$
13
12
r_k
11
10
$\exp(j2\pi f_r t)$
$r(t)$
X
$v(t)$

FIGURE 17A



$d_{0,1}$
0
0
$d_{1,1}$
0
$d_{N/I-1,1}$
3
$C_{0,1}$
$C_{N-1,1}$
5
7
s_k
8
u(t)
$e_{0,1}$
0
0
$e_{1,1}$
0
$e_{N/I-1,1}$
16
$x_{0,1}$
$x_{N-1,1}$
13
12
r_k
11
v(t)

FIGURE 17B

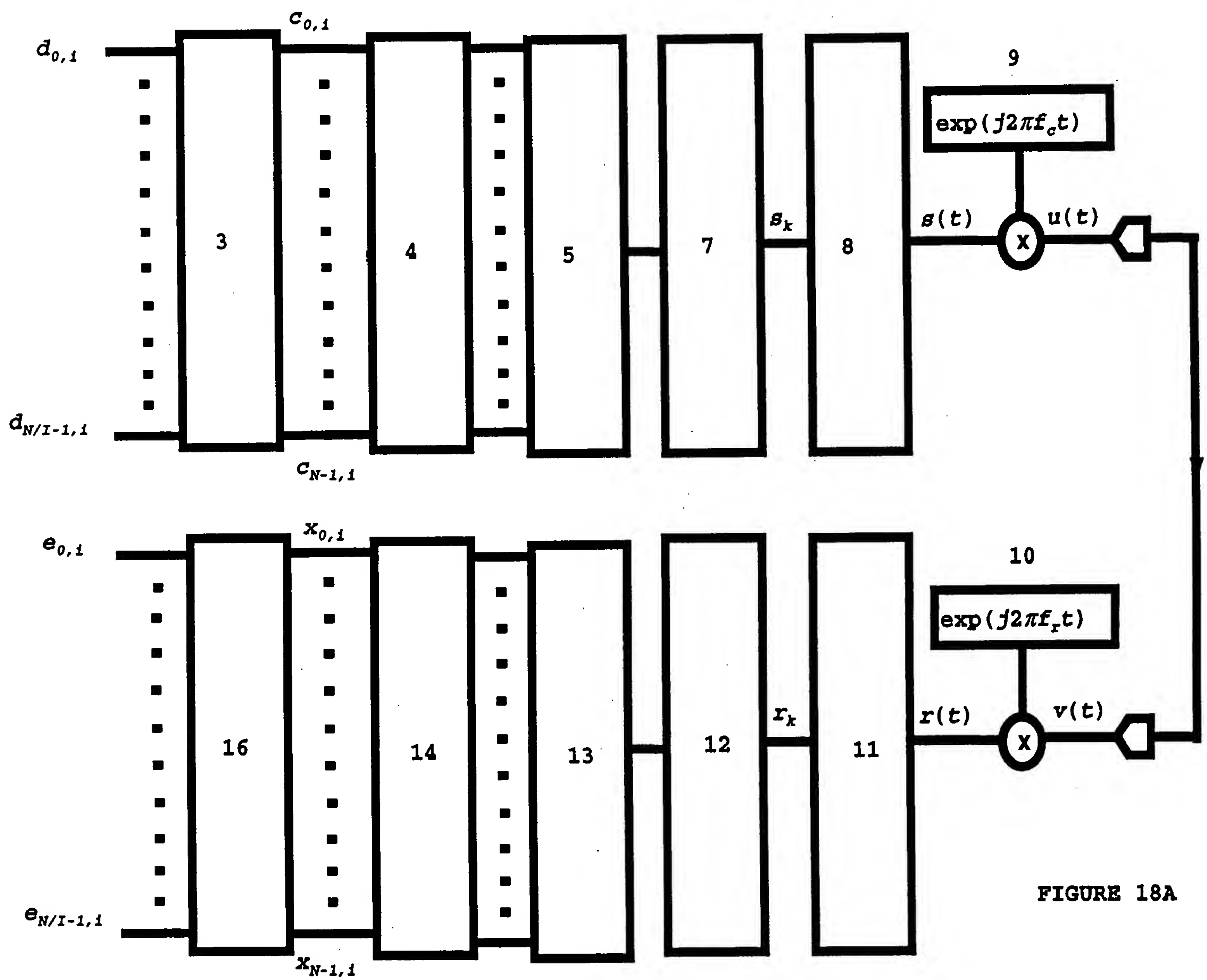
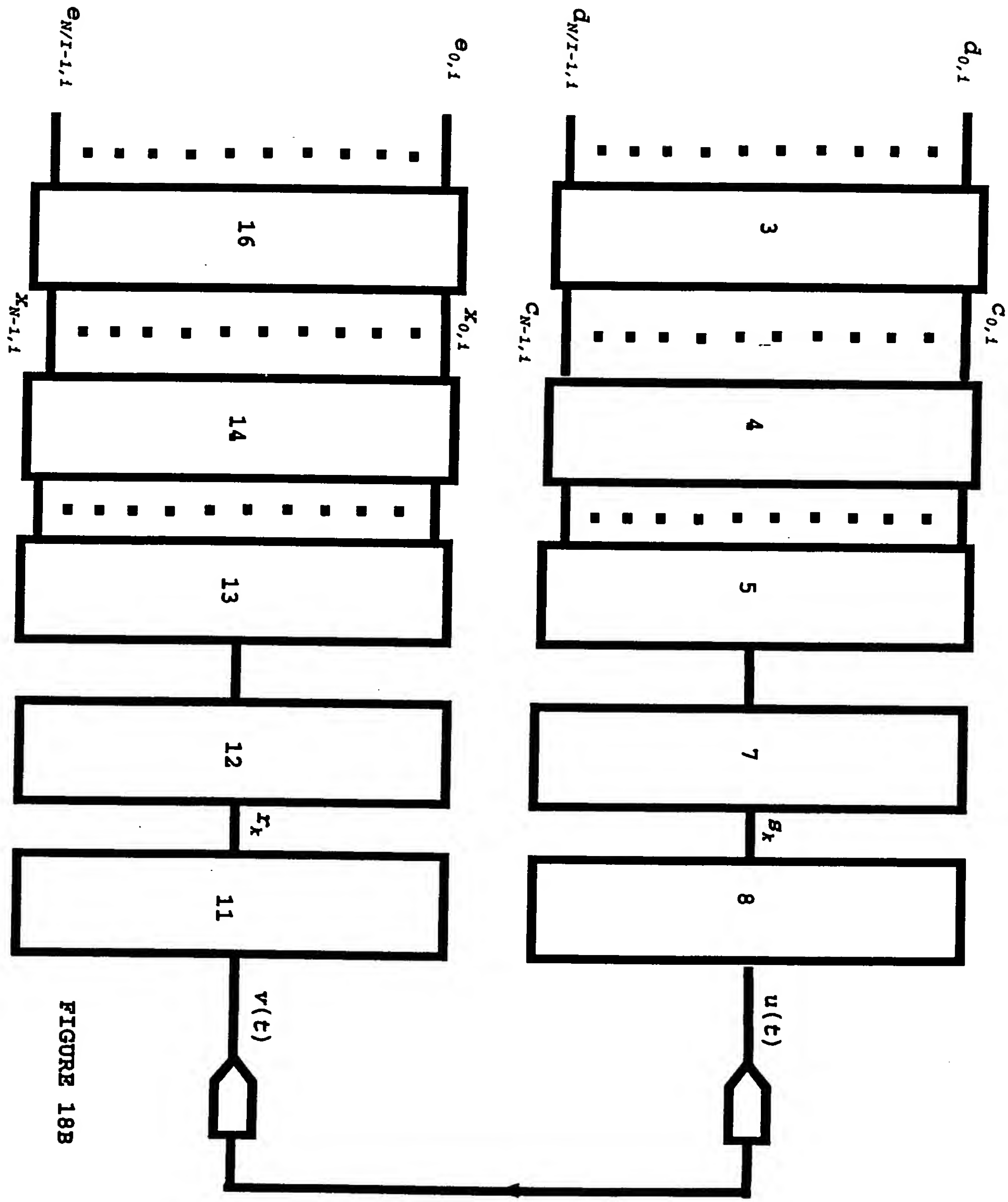

$d_{0,i}$
$d_{N/I-1,i}$
$c_{0,i}$
$c_{N-1,i}$
3
4
5
7
s_k
8
9
$\exp(j2\pi f_c t)$
$s(t)$
$u(t)$
X
$e_{0,i}$
$e_{N/I-1,i}$
$x_{0,i}$
$x_{N-1,i}$
16
14
13
12
r_k
11
10
$\exp(j2\pi f_r t)$
$r(t)$
$v(t)$
X

FIGURE 18A



$d_{0,1}$
$d_{N/I-1,1}$
3
$c_{0,1}$
$c_{N-1,1}$
4
5
7
g_k
8
u(t)
$e_{0,1}$
$e_{N/I-1,1}$
16
$x_{0,1}$
$x_{N-1,1}$
14
13
12
r_k
11
v(t)

FIGURE 18B

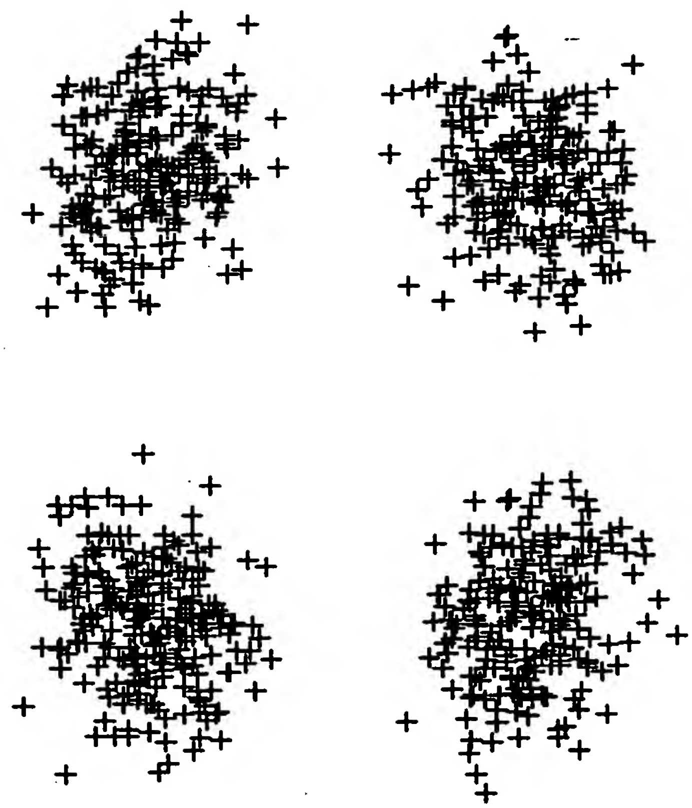


FIGURE 19

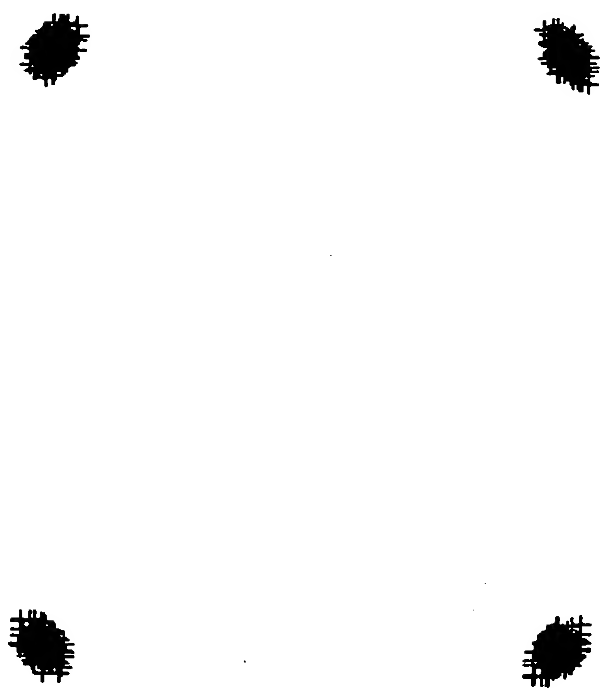


FIGURE 20

FIGURE 21

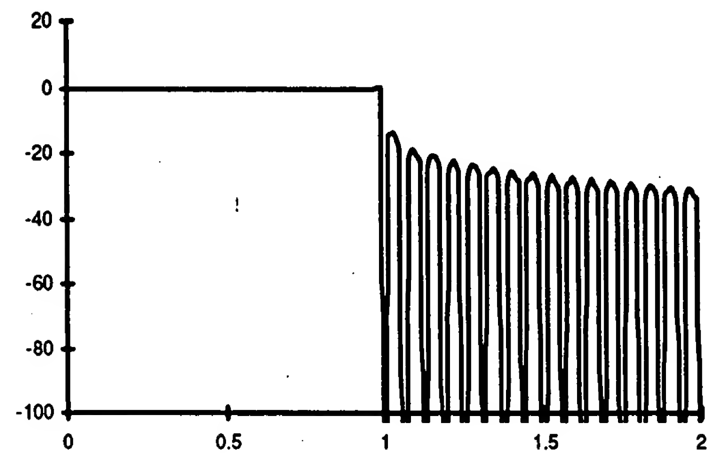


FIGURE 23A

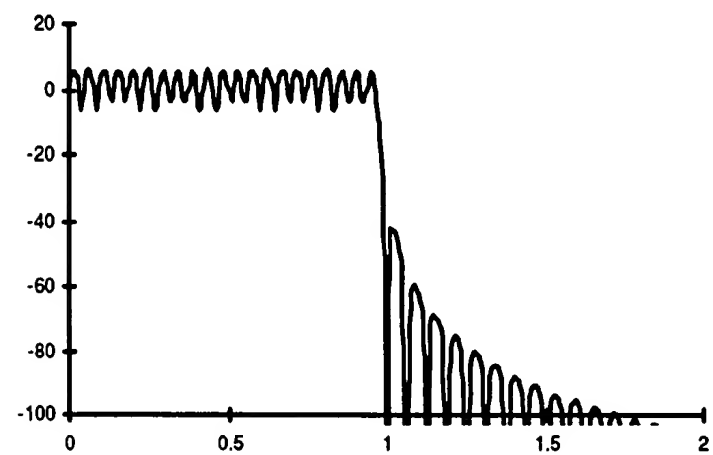


FIGURE 23B